GEOLOGICAL SURVEY OF CANADA

PAPER 86-21

METALLIC MINERALS ON THE DEEP SEABED

G.A. Gross and C.R. McLeod

1987

Energy, Mines and Resources Canada

Énergie, Mines et Ressources Canada

© Minister of Supply and Services Canada 1987

Available in Canada through

authorized bookstore agents and other bookstores

or by mail from

Canadian Government Publishing Centre
Supply and Services Canada
Ottawa, Canada K1A 0S9

and from

Geological Survey of Canada offices:

601 Booth Street
Ottawa, Canada K1A 0E8

3303-33rd Street N.W.,
Calgary, Alberta T2L 2A7

100 West Pender Street
Vancouver, British Columbia V6B 1R8

A deposit copy of this publication is also available
for reference in public libraries across Canada

Cat. No. M44-86/21E Canada: $10.00
ISBN 0-660-12612-5 Other countries: $12.00

Price subject to change without notice

Critical readers
D. Pasho
R. Chase
J.M. Franklin

Original manuscript received: 1986-07.
Final version approved for publication: 1987-04.

Cover

Unlithified iron-formation and stratafer sediment from the Red Sea graben, from left to right:

lenses of sulphide in siliceous facies of hydrolithic sediment; highly deformed iron oxide and siliceous clay beds; brecciated layers of unlithified iron oxide and siliceous clay.

Contents

Page	
1	Abstract/Résumé
2	Summary and conclusions/Sommaire et conclusions
24	Introduction
24	Map legend and symbols
25	Tectonic features
25	Volcanism
25	Mineral occurrences
25	Hydrothermal systems
26	Manganese nodules and crusts
26	Depositional environments
27	Physical and chemical properties of nodules
27	Mineralogy of nodules
27	Chemical composition of nodules
28	Distribution of manganese nodules
29	Estimates of manganese nodule resources
29	Cobalt in manganese-iron crusts
30	Mineral occurrences in the Mediterranean Sea and Red Sea
32	Mineral occurrences in the Indian Ocean
33	Mineral occurrences in the North Atlantic
37	Mineral occurrences in the South Atlantic
38	Mineral occurrences in the South Pacific
43	Mineral occurrences in the North Pacific
51	Mineral occurrences in the Juan de Fuca Ridge System
57	Information sources for Map 1659A
58	Selected bibliography
in pocket	Map 1659A — Distribution of metallic minerals on the deep seabed.

Tables

28	1. Average composition of abyssal nodules and encrustations from the Atlantic, Pacific and Indian oceans.
28	2. Average abundance of Mn, Fe, Ni, Co, and Cu in manganese nodules and crusts from different environments.

METALLIC MINERALS ON THE DEEP SEABED

Abstract

Seabed mineral deposits are composed mainly of manganese and iron oxide and sulphide minerals, and are classified as: manganese nodules and crusts; metalliferous sediments, including basal and surface facies, crusts, mounds, chimneys, and stacks at hydrothermal sites; and veins, stockworks, and replacement masses in bedrock. A world map, scale 1:40 million, shows mineral distribution in relation to major tectonic features, continental margins and areas 370 km from shore. Geological settings are described for about 250 mineral occurrences in the Atlantic, Pacific and Indian oceans, for manganese nodules, and for cobalt-rich manganese crusts. Exploration along the axes of spreading ridges has in general been selective and nonsystematic.

Manganese nodules containing 1.7 to 3.5% combined copper and nickel, in minimum abundance of 10 kg/m², and with high manganese-iron ratios, occur in the north equatorial and southwest Pacific, Atlantic and Indian oceans, where there is minimal detrital sedimentation, high biological productivity, and where hydrothermal fluids were likely sources of metals. Manganese crusts containing 0.3 to 1 % cobalt are common at depths of 800 to 2500 m on seamounts in the Central Pacific.

Metalliferous sediments are deposited by hydrothermal effusive systems that develop in the oceanic lithosphere where deep fracture zones coincide with anomalously high thermal gradients. Sulphide facies containing significant amounts of copper, zinc, lead, silver and gold are usually deposited near high temperature (50 to 400° C) hydrothermal vents, and commonly extend to siliceous oxide facies that are distal from vent sites and rich in iron, manganese, and nontronite clay or smectite. Many metalliferous facies on the seabed are similar in composition to iron-formations and related stratafer sediments mined on land.

Résumé

Les gîtes minéraux du fond marin se composent principalement de minéraux du type oxydes et sulfures de manganèse et de fer, et sont classés de la façon suivante : nodules et incrustations de manganèse; sédiments métallifères, y compris les faciès basaux et de surface, les incrustations, les monticules, cheminées et évents sur les sites hydrothermaux; et les filons et veines, stockwerks et masses de produits de substitution dans la roche de fond. Dans une carte du monde CGC carte 1659A, à l'échelle 1:40 000 000, est présentée la distribution des minéraux par rapport aux principaux éléments tectoniques, aux marges continentales et à des zones situées à 370 kms du littoral. On a décrit le cadre géologique de 250 venues minérales dans les océans Atlantique, Pacifique et Indien, relativement aux gisements de nodules de manganèse, et aux croûtes de manganèse enrichies en cobalt. En général, l'exploration le long des axes des dorsales océaniques créées par l'expansion crustale a été sélective et non systématique.

On rencontre dans la partie nord-équatoriale et le sud-ouest des océans Pacifique, Atlantique et Indien, où la sédimentation détritique est minimale, où la productivité biologique est élevée, et où les fluides hydrothermaux ont probablement été des sources de minéralisations métallifères, des nodules de manganèse contenant 1,7 à 3,5 % de cuivre et nickel combinés, et présentant une abondance minimale de 10 kg/m² et un rapport manganèse/fer élevé. On trouve souvent des croûtes de manganèse contenant 0,3 à 1 % de cobalt entre 800 et 2500 m au-dessous de la surface de la mer, sur des guyots, dans la région central du Pacifique.

Les sédiments métallifères sont déposés par des systèmes hydrothermaux de type effusif, qui apparaissent dans la lithospère océanique, là où des zones de fractures profondes coïncident avec des gradients thermiques anormalement élevés. Des faciès sulfurés contenant des quantités significatives de cuivre, de zinc, de plomb, d'argent et d'or se forment généralement par accumulation près d'évents hydrothermaux caractérisés par des températures élevées (50 à 400°C), et se prolongent généralement jusqu'à des faciès oxydés siliceux, éloignés des concentrations d'évents, et riches en fer, manganèse et argiles de type nontronite ou smectite. Les nombreux faciès métallifères que l'on rencontre sur le fond marin ont le même type de composition que les formations ferrifères et sédiments stratiformes apparentés, que l'on exploite dans les régions émergées.

SUMMARY

Technology developed in recent years has made it possible to explore mineral occurrences on the deep seabed that are analogous to many mineral deposits mined on land. This paper reviews the main types of metallic mineral occurrences on the deep seabed and their geological setting in relation to major geological features and their proximity to land areas. Brief notes on the mineral occurrences describe their type and depositional environment. A world map (MAP 1659A scale 1:40 million) shows islands and continents, areas 370 km from land, major tectonic features, the distribution of manganese nodules and crusts, various types of metalliferous sediments and crusts and areas where hydrothermal processes are now, or have been, active on the seafloor.

The main tectonic features shown on the map are the global distribution of spreading ridge systems, transform faults, and zones of subduction, thrusting and collision. The spreading ridges form linear belts where the earth's crust or plates are separating at rates of 1 to 17 cm/a. They are marked by linear fault zones, narrow troughs, horsts and grabens, and fault scarps, and are covered in places by volcanic flows and tuffs and various kinds of clastic and pelagic sediment. Hotsprings and extensive hydrothermal activity are found along the active spreading segments of the ridges and immense amounts of mineralized fluid and thermal energy are discharged on the seabed through open vents and fissures, from seepage springs and exhalation through the bedrock.

Transform faults are deep-seated fracture systems that separate segments of the spreading ridges and are focal areas for seismic activity, volcanism and effusive hydrothermal activity. Subduction zones are formed where one plate of the lithosphere is underthrust or overridden by another and are marked by thrust faulting, folding, uplift, seismic and volcanic activity. Block faulting is common in the back-arc basins that develop along the edges of the linear subduction belts. Seamounts, developed by a combination of geological processes, form circular, conical or irregular structures that rise 1000 m above the seafloor. Volcanism is an integral part of the development of the tectonic ridge systems, and lava flows, tuffs and pyroclastic rocks of intermediate to mafic and ultramafic composition are typical parts of the tectonic belts.

Two major metallogenetic types of mineral occurrences are commonly found on the seafloor, manganese nodules and crusts, and metalliferous sediments, crusts and mounds. The manganese nodules and crusts are widely distributed in the deep ocean basins mainly at depths greater than 2000 m and in some areas have a combined content of Cu,

SOMMAIRE

Les méthodes mises au point ces dernières années permettent d'explorer des venues minéralisées présentes sur les grands fonds marins et analogues à de nombreux gîtes minéraux exploités dans les régions émergées. Dans cet article, on examine les principaux types de venues métallifères existant sur les grands fonds, ainsi que leur cadre géologique, en fonction des principaux éléments géologiques et de leur proximité des régions émergées. Dans de brèves notes sur les venues minérales, on décrit les types de minéralisations et leur milieu de formation et d'accumulation. Dans une carte du monde (échelle 1/40 000 000), sont représentés les îles et continents, les zones situées à 370 km des terres, les principaux éléments tectoniques, la distribution des nodules et croûtes de manganèse, les divers types de sédiments et croûtes métallifères, ainsi que les régions connues, où des processus hydrothermaux ont eu lieu ou sont encore actifs sur le fond marin.

Les principaux détails tectoniques illustrés sur la carte sont la distribution globale des systèmes de dorsales médio-océaniques, des failles transformantes et des zones de subduction, de charriage et de collision. Les dorsales médio-océaniques forment des zones linéaires suivant lesquelles la croûte terrestre ou les plaques lithosphériques se fracturent, et se séparent à la vitesse de 17 cm par an. Ces dorsales se caractérisent par des zones de failles linéaires, d'étroites fosses ou dépressions, des horsts et grabens, et des escarpements de faille, et sont parfois recouvertes de coulées et tufs volcaniques et de diverses sortes de sédiments clastiques et pélagiques. On rencontre le long de sections des dorsales où le processus d'expansion crustale est actif, des sources chaudes et une activité hydrothermale importante; d'immenses quantités de fluides minéralisés et d'énergie thermique y sont libérées sur les fonds marins par des évents et fissures ouverts, des suintements et exhalations à travers les roches du socle.

Les failles transformantes sont des réseaux de fractures profondes, qui séparent des segments des dorsales médio-océaniques, et correspondent à des foyers d'activité sismique, de volcanisme et d'activité hydrothermale effusive. Des zones de subductions apparaissent à tout endroit où une plaque lithosphérique a subi un sous-charriage ou a été chevauchée par une autre plaque; elles sont caractérisées par des chevauchements, des plissements, des soulèvements, ainsi qu'une activité sismique et volcanique. Il existe un grand nombre de blocs faillés dans les bassins de la convexité des arcs insulaires qui se forment sur les bords des zones linéaires de subduction. Les guyots, dont la formation est due à la combinaison de plusieurs processus géologiques, constituent des structures circulaires, coniques ou irrégulières qui dominent d'environ 1000 m le fond marin. Le volcanisme fait intégralement partie de la phase de développement du réseau tectonique de dorsales; les coulées de laves, les tufs et les roches pyroclastiques de composition intermédiaire à mafique et ultramafique sont caractéristiques des zones tectoniques.

On rencontre souvent deux grands types métallogériques de venues minéralisées sur le fond marin; d'une part les nodules et croûtes de manganèse, d'autre part les sédiments, croûtes et monticules métallifères. Les croûtes et nodules de manganèse sont largement répandus sur les bassins océaniques pro-

Ni and Co greater than 1%. The metalliferous sediments, crusts and mounds located along fractures, faults and the spreading ridges, are formed by precipitation of Fe, Mn, Cu, Zn, Pb, Co, Ag, Au and other metals from hydrothermal fluids discharged on the seafloor.

Hydrothermal discharge from hotsprings, geysers, fumaroles and seepage through the sediment and lava on the seafloor is common along plate margins. The hot water discharged is part of convective circulation of seawater in the oceanic crust. In the course of this circulation the seawater and pore fluids dissolve metals and mineral constituents from the rocks through which they pass and, along with additional fluids and metals from magmatic sources, are discharged from vents and fractures in the seabed at temperatures as high as 400°C. These hydrothermal fluids transport metals in solution, and in colloidal size particles, and on emerging from vents and mixing with the cold seawater appear as turbulent cloudy geysers and plumes that are referred to as black or white smokers. This hydrothermal process is a major source of metals in the metalliferous sediments and crusts on the seafloor. Hydrothermal fluids deposit minerals in veins, stockworks, and fractures, and alter the composition of the bedrock along their circulation course. These hydrothermal processes are illustrated throughout the paper in the descriptions of the mineral occurrences and hydrothermal activity being explored on the seafloor.

Manganese nodules were dredged by the HMS Challenger expedition in the Pacific Ocean from 1872 to 1876, and their general distribution in the deeper parts of the ocean is shown on the map. The nodules and crusts are composed mainly of manganese and iron oxide, and range from micro-sized particles to potato-sized concretions that contain small amounts of Ni, Cu, Co, Mo, Pt and other metals. The manganese-rich crusts are similar in composition to the nodules associated with them, and consist of coatings and veneers a few millimetres thick to layered crusts several centimetres thick. The most extensive nodule fields are Mesozoic or younger, and nodules are forming at a slow rate at present. Nodules with a combined Ni and Cu content of 1% or more occur in the deep ocean basins in water depths of 4000 to 5000 m. Favourable conditions for nodule formation are found below the carbonate compensation depth in areas with low clastic sedimentation rates and high biological activity in the overlying surface waters. Their formation appears to be related to hydrothermal effusion in active tectonic belts, and many regional and local factors influence their development and distribution. Their size, shape, mineralogy, physical and chemical properties are highly variable and reflect the interplay of environmental factors and the dominant role of one or two genetic

fonds, surtout à plus de 2000 m de profondeur; dans certaines zones, ces nodules et croûtes ont une teneur combinée en Ci, Ni et Co supérieure à 1 %. Les sédiments, croûtes et monticules métallifères situés le long des fractures, failles et dorsales médio-océaniques, se forment par précipitation de Fe, Mn, Cu, Zn, Pb, Co, Ag, Au et d'autres métaux, à partir des fluides hydrothermaux qui se déversent sur les fonds marins.

Des solutions hydrothermales issues de sources chaudes, geysers, fumerolles et suintements à travers les sédiments et les laves recouvrant les fonds marins, sont fréquentes le long des marges des plaques lithosphériques. Les déversements d'eaux chaudes sur le fond marin font partie du flux convectif des eaux marines dans la croûte océanique. Durant leur circulation, les eaux marines et fluides interstitiels dissolvent les métaux et les constituants minéraux des roches qu'ils traversent, et sont libérés par des évents et fractures du fond marin, à des températures pouvant atteindre 400°C, en même temps que des quantités supplémentaires de fluides et métaux d'origine magmatique. Ces fluides hydrothermaux transportent des métaux en solution et des particules colloïdales, et, lorsqu'ils émergent des évents et se mêlent aux eaux marines froides, se manifestent par des geysers et panaches turbulents d'aspect trouble, auxquels on donne le nom de "fumeurs" noirs ou blancs. Ces processus hydrothermaux constituent une importante source de métaux pour les sédiments métallifères et croûtes qui recouvrent le fond marin. Les fluides hydrothermaux déposent des minéraux dans les filons et veines, stockwerks et fractures, et modifient la composition du socle sur leur trajet. Dans tout cet article, les processus hydrothermaux sont expliqués par des descriptions des venues minéralisées et zones d'activité hydrothermale actuellement explorées sur les fonds marins.

Entre 1872 et 1876, au cours de l'expédition du navire océanographique HMS Challenger dans le Pacifique, ont été recueillis des nodules de manganèse par dragage du fond; la carte indique la distribution générale de ces nodules dans les parties les plus profondes de l'océan. Les nodules et croûtes sont principalement composés d'oxydes de manganèse et de fer, et vont de particules microscopiques à des concrétions de la taille d'une pomme de terre, contenant de petites quantités de Ni, Cu, Co, Mo, Pt et d'autres métaux. Les croûtes manganésifères ont une composition semblable à celle des nodules qui leur sont associés, et sont parfois des enduits et placages de quelques millimètres d'épaisseur, ou bien des croûtes stratifiées pouvant atteindre plusieurs centimètres d'épaisseur. Les plus vastes champs de nodules sont d'âge mésozoïque ou plus récents, et des nodules continuent à se former actuellement de façon très lente. On rencontre dans les bassins océaniques profonds entre 4000 et 5000 m de profondeur, des nodules caractérisés par une teneur combinée en Ni et Cu de 18 % ou davantage. On rencontre des conditions favorables à la formation de nodules, au-dessous de la profondeur de compensation des carbonates, dans des zones caractérisées par un faible taux de sédimentation clastique et par une activité biologique intense dans les eaux sus-jacentes superficielles. Il semble que la formation des nodules soit associée à des effusions hydrothermales dans les zones tectoniques actives, et que de nombreux facteurs régionaux et locaux influent sur leur développement et sur leur distribution. Leurs dimensions, forme, minéralogie et propriétés

processes. The source of metals in the nodules is attributed to a number of processes, singularly, or in combination, including hydrothermal solutions and hydrogenous sources, leaching from the bottom sediments and volcanic rocks during their diagenesis and consolidation, and transport of detrital and colloidal particles during weathering of a landmass.

Manganese nodules are commonly spheroidal to ellipsoidal, botryoidal, discoidal, tabular or faceted in shape, 2 to 5 cm in their greatest dimension, and range from micronodules less than 1 mm in size to masses 1 m in diameter, weighing a tonne. Nodules form around a variety of nuclei, and their internal structure and textures vary from concentrically layered to massive microlaminae forming uniform layers or arcuate cusps from 0.25 to 10 mm in thickness. Textures range from granular, globular to dendritic with acicular to radial crystal habits. Growth rates average about 5 mm in a million years and may range from 1 to 50 mm in that time.

Nodules are commonly earthy black, bluish-black or deep brown, with a vitreous lustre and are composed of porous fine grained crystalline aggregates, colloidal-size particles and amorphous material. Their hardness ranges from 1 to 4 and averages about 3 on the Mohs scale of 10. Nodules containing less than 3% carbonate are brittle and friable and their average density is 1.95 g/cc, and the mean value for porosity is 58.3 %. Todorokite, birnessite, psilomelane and hollandite are the most common of the large number of complex hydrous manganese oxide mineral phases identified in nodules. Most of the iron associated with the manganese minerals occurs in goethite, lepidocrocite, hematite, maghemite and amorphous hydrated ferric iron oxide gel.

Major elements in dry nodules are O, Mn, Fe, Si, and lesser amounts of Al, Ca, Na, and Mg. Ni, Cu, Co, and Pt are of most interest among the host of minor or trace elements. Relative to average crustal rocks nodules are enriched in Mn, Fe, Ni, Cu, Co, Zn, Mo, Ba and Pb. The abundance of constituents varies greatly in nodules from different environments on seamounts, abyssal plains, continental margins, active spreading ridges or plateaus. Ratios of Mn to Fe range from 3.94 to 0.67 in the deeper ocean basins, but are highly variable on continental margins where they range up to 28. The average contents of Ni, Cu, and Co, are consistently higher in nodules from the Pacific Ocean, intermediate in the Indian Ocean, and lowest in nodules from the Atlantic Ocean, with a few local exceptions.

Large areas where nodules are abundant and contain appreciable Ni, Cu and Co are located within 30° of the Equator in the Pacific and Indian Oceans and in the south and southeastern Pacific.

physiques et chimiques, sont très variables et reflètent l'interaction des facteurs environnementaux, et le rôle dominant d'un ou deux processus génétiques. On attribue la source des métaux présents dans les nodules à un certain nombre de processus agissant séparément ou de concert, en particulier aux effets des solutions hydrothermales et des sources hydrogénées, qui lixivient les sédiments et les roches volcaniques du fond marin en les traversant durant leur diagénèse et leur consolidation, et au transport de particules détritiques et colloïdales durant la météorisation et l'altération des terres émergées.

Les nodules de manganèse sont généralement de type sphéroïdal à ellipsoïdal, botryoïde, discoïdal, tabulaire ou à facettes, ont un grand axe de 2 à 5 cm, et leur taille peut aller de micronodules de moins de 1 mm à des masses de 1 m de diamètre pesant près d'une tonne. Les nodules se forment autour de divers noyaux; leurs structures et textures internes sont variables; on observe de très fines stratifications concentriques, ou bien des straticules massives constituant des couches uniformes ou des structures en croissant de 0,25 à 10 µm d'épaisseur. Leur texture peut être grenue, sphérolitique, dendritique, ou bien aciculaire à rayonnante. Ils augmentent de taille à la vitesse de 1 à 50 mm par million d'années, et en moyenne de 5 mm durant cet intervalle de temps.

Les nodules sont souvent d'un noir terreux ou noir bleuâtre, ou sont brun sombre, ont un éclat vitreux, et sont composés d'agrégats microcristallins poreux, de particules colloïdales et de produits amorphes. Dans l'échelle de dureté de Mohs, comprise entre 1 et 10, ils se situent entre 1 et 4 et atteignent en moyenne 3. Les nodules contenant moins de 3 % de carbonates sont fragiles et friables; leur masse volumique moyenne est de 1,95 g/cm^3, et leur porosité moyenne de 58,3 %. La todorokite, la birnessite, la psilomélane et la hollandite sont les plus courantes parmi le grand nombre de phases minérales oxydées complexes et hydratées manganésifères, que l'on identifie dans les nodules. La plupart du temps, le fer associé aux minéraux manganésifères se présente sous forme de goethite, de lépidocrocite, d'hématite, de maghémite, et sous forme de gels d'oxydes ferriques, amorphes et hydratés.

Les principaux éléments dont se composent les nodules secs sont O, Mn, Fe, Si et des quantités accessoires d'Al, Ca, Na, Mg, Ni, Cu, Co et Pt, parmi une quantité d'éléments traces. Par rapport à la composition moyenne des roches de la couche terrestre, les nodules sont enrichis en Mn, Fe, Ni, Cu, Co, Zn, Mo, Ba et Pb. L'abondance de chaque constituant varie de façon importante dans les nodules suivant que ceux-ci proviennent de guyots, de plaines abyssales, de marges continentales, de dorsales médio-océaniques actives, ou de plateaux. Dans les bassins océaniques profonds, le rapport Mn/Fe se situe entre 3,94 et 0,67, mais il est très variable sur les marges continentales, où il peut atteindre 28. Les teneurs moyennes en Ni, Cu et Co sont pratiquement toujours plus élevées dans les nodules provenant de l'océan Pacifique, intermédiaires dans ceux provenant de l'océan Indien, et les plus faibles dans les nodules provenant de l'océan Atlantique; toutefois, il existe quelques exceptions à l'échelle locale.

De vastes superficies de nodules contenant des quantités appréciables de Ni, Cu et Co, se trouvent dans une zone comprise entre 0 et 30° à partir de l'équateur dans les océans Paci-

Sample data and information on nodules are most extensive in the northeast Pacific, in an area bounded by the Clarion and Clipperton fracture zones. Concentrations of nodules ranging up to 30 kg/m^2 are more consistent in this area than in most of the others and the combined content of Ni and Cu in the nodules is usually in excess of 3%. Here bottom sediments are mainly siliceous ooze and red clay. Estimates based on assumptions of an average concentration of 9 kg/m^2 over 6 000 000 km^2 of ocean floor indicate a potential resource of 38 billion tonnes (dry weight) of nodules averaging 29 % Mn, 0.3 % Co, 1.77 % Ni, and 1.4 % Cu, which would contain 11 billion tonnes of Mn, 115 million tonnes of Co, 650 million tonnes of Ni, and 520 million tonnes of Cu.

Other nodule areas with a significant content of Ni and Cu have been reported southwest of Hawaii, in the South Pacific and between the East Pacific Rise and South America. Concentrations of nodules of interest as resources are also present in the Indian Ocean, and scattered concentrations are reported southwest of Australia. Nodules are sparsely and irregularly distributed through large areas of the Atlantic Ocean. The Blake Plateau east of Florida is of most interest, because the nodules and crusts occur in relatively shallow water, and have high Mn to Fe ratios. Nodules on the Tyrrhenian seabed off the west coast of Italy also have high Mn to Fe ratios. Interesting concentrations of nodules have been reported south and southwest of Africa. Estimates of potential resources of nodules in the world, based on a minimum abundance of 10 kg/m^2 and a minimum combined grade of 1.76% Cu and Ni range from 14 to 99 billion tonnes.

Co-rich Mn crusts are widely distributed on the slopes of seamounts and islands in the equatorial Pacific, on the Blake Plateau in the northwest Atlantic, and with denser concentrations of nodules in many ocean basins. Exploration shows that the most favourable areas for Co bearing crusts lie on seamounts older than 25 Ma, within water depths of 800 to 2400 m, from 5 to 15° from the equatorial zone, and in areas where two generations of crusts with ages from 16 to 9 Ma and 8 Ma or younger are present. Co concentrations in Mn -Fe crusts and nodules in the Mid-Pacific Mountains and Line Islands areas increase from less than 0.4 % at water depths of 4000 m, to 1.2 % on seamount slopes and summits less than 2500 m in depth. The thickness of crusts ranges from 2 cm in the upper slope areas to 9 cm in the lower areas and may contain more than 16 kg (equivalent dry weight) of crustal material per square metre of crustal surface.

The composition of crusts varies greatly with 15 to 31 % Mn, 7 to 18 % Fe , Mn/Fe ratios from 1.0 to 3.4, and Co content as high as 2 % and averaging 0.8 %. The crusts contain significant amounts

fique et Indien et dans les parties sud, centrale et sud-est de l'océan Pacifique. Grâce à des échantillonnages, on a obtenu le plus grand nombre de données et de renseignements sur les nodules présents dans le nord-est du Pacifique, dans une zone délimitée par les zones de fractures de Clarion et de Clipperton. Les concentrations de nodules, qui peuvent atteindre 30 kg/m^2, sont plus uniformes dans cette région que dans la plupart des autres; les nodules y ont généralement une teneur combinée en Ni et Cu supérieure à 3 %. Dans cette région riche en nodules, les sédiments du fond sont principalement des vases siliceuses et de l'argile rouge. Si l'on postule une concentration moyenne de 9 kg/m^2 sur 6 000 000 de km^2 du fond de l'océan, les calculs indiquent l'existence de ressources potentielles équivalentes à 38 milliards de tonnes (en poids sec) de nodules contenant en moyenne 29 % de Mn, 0,9 % de Co, 1,77 % de Ni et 1,4 % de Cu, ce qui correspondrait à 11 milliards de tonnes de Mn, 150 millions de tonnes de Co, 650 millions de tonnes de Ni et 520 millions de tonnes de Cu.

On a signalé l'existence d'autres zones de nodules caractérisés par une teneur notable en Ni et Cu au sud-ouest de Hawaii dans le Pacifique du Sud, et entre la dorsale du Pacifique de l'Est et l'Amérique du Sud. Il existe aussi dans l'océan Indien des concentrations de nodules qui pourraient être considérées comme des ressources potentielles, et l'on a signalé des concentrations diffuses au sud-ouest de l'Australie. Des nodules sont distribués en petites quantités et sporadiquement dans de vastes régions de l'Atlantique. Le plateaux Blake à l'est de la Floride est particulièrement intéressant, parce que les nodules et croûtes existent en eau relativement peu profonde, et sont caractérisés par des rapports Mn/Fe élevés. Les nodules que l'on trouve sur le fond de la mer Tyrrhénienne, au large des côtes occidentales de l'Italie, présentent aussi des rapports Mn/Fe élevés. On a signalé des concentrations intéressantes de nodules au sud et au sud-ouest de l'Afrique. Des estimations faites des ressources mondiales potentielles de nodules, en admettant une abondance minimum de 10 kg/m^2 et une teneur minimale combinée de 1,76 % en Cu et Ni, indiquent des réserves comprises entre 14 et 99 milliards de tonnes.

Les croûtes de Mn riches en Co occupent de vastes surfaces, le long des versants des guyots et des îles, dans la région équatoriale de l'océan Pacifique, et sur le plateau Blake dans le nord-ouest de l'océan Atlantique, et l'on rencontre des concentrations plus denses de nodules dans de nombreux bassins océaniques. L'exploration indique que les zones les plus favorables à l'existence de croûtes cobaltifères se trouvent sur des guyots datant de plus de 25 ma, entre 800 et 2400 m de profondeur, entre 5° et 15° à partir de la zone équatoriale, et dans des régions où coexistent deux générations de croûtes datant respectivement de 16 à 9 Ma et de 8 Ma ou moins. Dans la région du chaînon médio-Pacifique et des îles de la Ligne, les concentrations de cobalt dans les croûtes et nodules contenant Mn-Fe augmentent de moins de 0,4 % à la profondeur de 4000 m, à 1,2 % sur les versants des guyots et sur les sommets se trouvant à moins de 2500 m de profondeur à partir de la surface de la mer. L'épaisseur des croûtes se situe entre 2 cm dans la partie supérieure du talus et 9 cm au bas des pentes; il peut y avoir plus de 16 kg (en poids sec équivalent) de matériaux constitutifs des croûtes, par mètre carré de surface recouverte d'une croûte.

of Ni, Pb, Ce, Mo, V, and Pt. Maximum Pt content occurs in crusts at water depths of 1100 to 1250 m and ranges from 0.6 ppm in the older crusts to 0.3 ppm in the younger crusts, and varies directly with the amount of Co and Ni. Estimates of resource potential for the Co-rich Mn crusts in the Exclusive Economic Zones of the United States Trust and affiliated Territories in the Pacific are based on maximum crust thickness of 1.0 to 2.5 cm, an average dry density of 1.33 g/cc and Co content ranging from 0.78 % to 1.18 %, Ni content from 0.39 to 0.53 %, Mn from 21.4 to 26.56 %, and Pt content from 0.6 ppm in the older crusts to 0.3 ppm in the younger crusts.

Co bearing Mn crusts cover thousands of square kilometres on the Blake Plateau and other areas on the Sierra Leone Rise and the east flank of the Mid-Atlantic Ridge where crusts have a Co content up to 1%.

Deposits of metalliferous sediment are forming at several locations in the Mediterranean Sea along a subduction zone where the African Plate is being thrust beneath the Aegean Plate. The island of Santorini, or Thera, located on the Aegean plate, is part of an island arc that extends between Greece and Turkey. Submarine mineral deposition related to volcanic and hydrothermal activity was observed off Santorini Island as early as 1650. Fe-rich siliceous sediments are being precipitated in several bays within the Santorini Caldera by warm submarine springs that represent a late phase of volcanic activity. The gel-like siliceous metalliferous sediment up to 3 m thick contains about 33 % Fe_2O_3, from 20 to 65 % SiO_2, 2 to 4 % CaO and MgO, 2 to 10 % Na_2O and K_2O and minor amounts of Zn, Mn, V, Cr, Cu, Pb, Sc, and Mo. The metalliferous mud being deposited at Santorini by hydrothermal effusive processes is a primary sedimentary facies or progenitor of an Algoma type iron-formation.

Volcano Island in the Tyrrhenian Sea between Italy and Sicily is the site of extensive hydrothermal effusive activity. Pyrite, marcasite, alunite, opal and sulphur cement tuff beds, and extensive amounts of iron sulphide have been deposited as framboidal pyrite. Goethite crusts around the fumarolic vents are formed by oxidation of sulphide minerals and primary deposition of iron oxide. Two facies types have been identified in this shallow marine environment, one composed of pyrite, marcasite, chalcopyrite, gypsum, iron and manganese oxides and clay minerals, and another of iron and manganese oxides, sulphate and clay minerals in the outer zones around the fumaroles. Sulphide-rich sediments (21 % iron sulphide) up to 6 m thick contain As, Hg,Bi, and Te. Temperatures of the fumarolic waters range from 210°C in La Fossa crater to about 100°C in Baia di Levant.

La composition des croûtes varie fortement, avec des taux de 15 à 31 % de Mn, 7 à 18 % de Fe, un rapport Mn/Fe compris entre 1 et 3,4, et un taux de Co pouvant atteindre 2 % et égal en moyenne à 0,8 %. Les croûtes contiennent des quantités notables de Ni, Pb, Ce, Mo, V, et Pt. On rencontre les concentrations maximales de Pt dans les croûtes entre 1100 et 1250 m de profondeur d'eau; elles se situent entre 0,6 ppm dans les croûtes anciennes et 0,3 ppm dans les plus récentes, et varient directement en fonction des concentrations de Co et Ni. Les estimations des réserves potentielles que représentent les croûtes manganésifères riches en cobalt que l'on trouve dans les zones économiques exclusives des territoires sous la tutelle des États-Unis et territoires affiliés du Pacifique, ont été faites en postulant que les croûtes ont une épaisseur maximum de 1,0 à 2,5 cm, une masse volumique moyenne (du produit sec) de 1,33 g/cm^3 et une teneur en Co comprise entre 0,78 % et 1,18 %, une teneur en Ni comprise entre 0,39 et 0,53 %, une teneur en Mn comprise entre 21,4 et 26,56 %, et une teneur en Pt comprise entre 0,6 ppm pour les croûtes anciennes et 0,3 ppm pour les plus récentes.

Les croûtes manganésifères contenant du Co couvrent des milliers de kilomètres carrés sur le plateau Blake et d'autres régions de la dorsale de la Sierra Leone et sur le versant est de la dorsale médio-Atlantique, où ces croûtes ont une teneur en cobalt atteignant 1 %.

En plusieurs endroits de la Méditerranée, se forment des dépôts de sédiments métallifères, le long d'une zone de subduction où la plaque africaine est entraînée sous la plaque égéenne. L'île de Santorini, ou Thera, située sur la plaque égéenne, fait partie d'un arc insulaire qui s'étend entre la Grèce et la Turquie. Dès 1650, on avait observé au large de l'île de Santorini le dépôt sous-marin de minéraux, en rapport avec l'activité volcanique et hydrothermale. Des sédiments siliceux ferrifères précipitent dans plusieurs baies de la caldeira de Santorini, à partir de sources chaudes sous-marines qui représentent une phase tardive d'activité volcanique. Le sédiment métallifère siliceux, qui a l'apparence d'un gel et peut atteindre 3 m d'épaisseur, contient environ 33 % de Fe_2O_3, 20 à 65 % de SiO_2, 2 à 4 % de CaO et MgO, 2 à 10 % de Na_2O et K_2O, et des quantités accessoires de Zn, Mn, V, Cr, Cu, Pb, Sc et Mo. Les boues métallifères que déposent à Santorini les processus effusifs hydrothermaux correspondent à un faciès sédimentaire primaire, ou faciès préliminaire d'une formation ferrifère de type Algoma.

L'île Vulcano, située dans la mer Tyrrhénienne entre l'Italie et la Sicile, est le site d'une importante activité effusive de type hydrothermal. À cet endroit, se sont déposés de la pyrite, de la marcassite, de l'alunite, de l'opale et des lits de tufs à ciment sulfuré, et des quantités importantes de sulfures de fer, ces derniers sous forme de pyrite framboïdale. Des croûtes de goethite se sont formées autour des évents de fumerolles, par oxydation des minéraux sulfurés et dépôts primaires d'oxydes de fer. On a identifié deux types de faciès dans cet environnement marin peu profond; l'un contenant de la pyrite, de la marcassite, de la chalcopyrite, du gypse, et des oxydes de fer et manganèse, et des minéraux argileux, l'autre contenant des oxydes de fer et de manganèse, et des minéraux sulfatés et argileux dans les zones extérieures concentriques aux fumerolles. Des sédiments sulfurés (21 % de sulfures de fer), qui peuvent

Copper sulphide minerals of volcanogenic exhalative origin at Palinuro Seamount in the Tyrrhenian Sea are mixed with metalliferous ooze and indurated sulphide crust that are associated with sedimentary ooze of organic and volcanic origin. The mineral assemblage includes pyrite, barite, tetrahedrite, tennantite, native copper and silver, bismuthinite and stibnite.

More than 20 submarine volcanoes are located in an ancient basin in the Tyrrhenian Sea that is up to 4000 m deep. Deposits of manganese nodules in quantities of 2 to 3 kg/m^2 in the shallow (100 m) water between volcanoes contain about 41 % Mn.

The Red Sea Graben, more than 2000 km long, 300 km wide, and 2200 m deep, was formed by arching and thinning of the continental lithosphere between the Nubian and Arabian shields. Exploration of more than 20 deep basins in the Red Sea Graben that contain metalliferous sediment was initiated in 1964 with the discovery of hot brines on the seafloor by scientists aboard the *RRS Discovery*. Spreading and rifting at the rate of 2 to 3 cm per year began in the late Eocene and was accompanied by reef building, deposition of chert, conglomerate, sandstone, shale, salt, anhydrite, diatomite, limestone and the extrusion of basalt. Intermittent hydrothermal effusion along the axial part of the trench has led to deposition over the last 25 000 years of metalliferous sediment that is remarkably similar in composition to some facies of Algoma type iron-formation and regarded by many as a modern progenitor of these chemical sediments.

Thin layered (1 mm to 20 cm) multicoloured metalliferous chemical sediment 5 to 30 m thick covers an area of 65 km^2 at depths of 2000 to 2200 m in the Atlantis II Deep along the axis of the middle segment of the rift system west of Jeddah, Saudi Arabia. The sequence of metalliferous sediment consists of finely laminated iron and manganese oxide facies with interlayered and disseminated sulphide facies. A generalized stratigraphic sequence includes basal basalt flows overlain by 3 m of finely crystalline hematite and limonite with minor iron sulphide and sulphate minerals, followed by sulphate and silicate facies , hematite and goethite layers, interlayered oxide, silicate and sulphide-rich facies, breccia layers containing unlithified hematite fragments cemented by sulphide and silicate material, and an upper part, 3 to 4 m thick, that consists of semiliquid amorphous sulphide and silicate layers and various facies of amorphous silicates, sulphidic mud, iron-rich montmorillonite clay facies, and hydrated iron oxide (lepidocrocite) facies. In the southwest part of the basin, unlithified layered sediments are re-brecciated and disturbed and cut by veins formed by late stage hydro-

atteindre 6 m d'épaisseur, contiennent As, Hg, Bi et Te. La température de l'eau s'échappant des fumerolles se situe entre 210°C dans le cratère La Fossa, et environ 100°C à Baia di Levante.

À l'emplacement du guyot Palinuro dans le mer Tyrrhénienne, les minéraux sulfurés cuprifères d'origine volcanique-exhalative, se mélangent à des boues métallifères et à une croûte sulfurée indurée, toutes deux associées à des vases sédimentaires d'origine organique et volcanique. L'assemblage minéral comprend de la pyrite, de la barytine, de la tétrahédrite, de la tennantite, du cuivre et de l'argent natifs, de la bismuthinite et de la stibnite.

Il existe plus de 20 volcans sous-marins dans un ancien bassin de la mer Tyrrhénienne, qui atteint 4000 m de profondeur. Les gîtes de nodules de manganèse, qui en contiennent 2 à 3 kg/m^2 dans les eaux peu profondes (100 m) séparant les volcans, renferment environ 41 % de Mn.

Le graben de la mer Rouge, qui a plus de 2000 km de longueur, 300 km de largeur et 2200 m de profondeur, s'est formé par inflexion et amincissement de la lithosphère continentale entre le bouclier Nubien et le bouclier Arabe. En 1964, a commencé l'exploration de plus de 20 bassins profonds du graben de la mer Rouge contenant des sédiments métallifères; c'est ainsi qu'ont été découvertes des sources salines chaudes sur le fond marin par des chercheurs travaillant à bord du navire océanographique *RRS Discovery*. Durant l'Éocène supérieur, ont commencé les processus d'expansion et de fissuration de la croûte terrestre, à la vitesse de 2 à 3 cm par an; ils ont été accompagnés de la formation de récifs, du dépôt de cherts, de conglomérats, de grès, d'argiles litées, de sel, d'anhydrite, de diatomite, de calcaires, et aussi de l'extrusion de basaltes. Des effusions hydrothermales se produisant de façon intermittente, suivant l'axe de la fosse, ont permis au cours des 25 000 dernières années le dépôt de sédiments métallifères, dont la composition est remarquablement similaire à celle de certains faciès des formations ferrifères de type Algoma, et qui sont considérés par un grand nombre de chercheurs comme la phase moderne préliminaire de ces sédiments chimiques.

Les sédiments chimiques métallifères, multicolores, finement stratifiés (1 mm à 20 cm), atteignant 5 à 30 cm d'épaisseur, recouvrent une superficie de 65 km^2 entre 2000 et 2200 m de profondeur dans l'abysse Atlantis II, suivant l'axe de la portion intermédiaire du réseau de fossés tectoniques (rifts), à l'ouest de Jeddah en Arabie Saoudite. La succession de sédiments métallifères est constituée de faciès à oxydes de fer et de manganèse, finement laminés, dans lesquels sont interstratifiés et disséminés des faciès sulfurés. De façon générale, la succession stratigraphique comprend : à sa base, des coulées basaltiques, recouvertes de 3 m d'hématite et de limonite microcristallines accompagnées de quantités accessoires de sulfures et sulfates de fer; puis des faciès à sulfates et silicates; des couches d'hématite et de goethite, des oxydes interstratifiées; des faciès riches en silicates et sulfures, des couches bréchiques contenant des fragments d'hématite non lithifiés, cimentés par des matériaux sulfurés et silicatés; et au sommet, un niveau de 3 à 4 m d'épaisseur constitué de couches semiliquides de sulfures et silicates amorphes, de divers faciès avec silicates amorphes et boues sulfureuses, d'un faciès montmo-

thermal venting. Hematite-magnetite-pyroxene mineral assemblages have developed during late stages of recrystallization. Pyrite, sphalerite, and chalcopyrite are the most common sulphide minerals and are associated with talc, magnesium-rich smectite clay, anhydrite and gypsum, iron and manganese oxide minerals and amorphous silica.

The Atlantis II Deep contains the largest concentration of metals in the Red Sea graben. A deposit of layered unconsolidated siliceous chemical sediment rich in Fe, Mn and sulphide minerals about 10 m thick, is distributed over an area of 5 by 13 km at depths of 2000 to 2200 m. It contains more than 32 Mt of metals including 0.4 Mt or 1.3% Cu (dry weight), 1.7 Mt or 3.4% Zn, 0.1% Pb, 29% Fe, 54 ppm or 5000 t of Ag, 0.5 ppm Au and some Co.

Mineral occurrences in the Indian Ocean consist mainly of metalliferous sediment and sulphide stockworks. Hydrothermal metalliferous sediment associated with basalt lava in the median valley of the Gulf of Aden consists of spongy brown to hard black coatings of iron and manganese oxide containing up to 45 % Mn and friable green massive smectite. Similar occurrences of Mn-Fe oxide occur on the Carlsberg Ridge and the Owen Fracture Zone. Basal metalliferous sediment of Middle Miocene age in the Wharton Basin is about 60 m thick and consists of zeolite and Mn-Fe oxide clay facies. It grades to an iron-manganese oxide-rich facies, about 5 m thick, that rests on altered basalt. Basal iron oxide facies 2 m thick are overlain by Eocene calcareous ooze at Ninety East Ridge, and Mn-Fe crusts and sediment occur at other sites. Samples from near the intersection of a rift valley and the Vitias Fracture Zone contain veins of sulphide minerals.

Abundant evidence of hydrothermal effusive processes is found throughout the Atlantic Ocean in the various types of mineral occurrences described. Present and recent hydrothermal activity has been reported along the Mid-Atlantic Ridge and on a few seamounts. Many of the occurrences of basal metalliferous sediment near the margins of continents were deposited during early stages of ridge development. Large patches of manganese nodules also appear to be related to hydrothermal effusion originating along the rift structures.

Hydrothermal activity in Iceland is closely associated with volcanism on a segment of the Mid-Atlantic Ridge (MAR) and has been an important source of energy for many years. Iron-rich (14%) metalliferous sediment in the crestal region of the Median Valley of the Mid-Atlantic Ridge is enriched in As and Hg and contains minor amounts of Mn, Cu, Cr, Ni, Pb, B, Cd, and V in the amorphous iron oxide grains. Ferruginous sediment occurs in the Eastern and Western Mountain area and manrillonitique ferrifère, et d'un faciès à oxydes de fer hydratés (lépidocrocite). Dans la partie sud-ouest du bassin, des sédiments stratifiés et non lithifiés ont été à nouveau dérangés et transformés en brèches, et recoupés par des veines formées lors d'une phase tardive d'effusion hydrothermale. Des assemblages minéraux à hématite-magnétite-pyroxène sont apparus durant les dernières étapes de la recristallisation. La pyrite, la sphalérite, et la chalcopyrite sont les minéraux sulfurés les plus communs, et sont associés à du talc, à des argiles smectiques riches en magnésium, à de l'anhydrite et à du gypse, à des oxydes de fer et de manganèse, et à de la silice amorphe.

La fosse abyssale Atlantis II contient les plus fortes concentrations métalliques, dans le graben de la mer Rouge. Un dépôt de sédiments chimiques siliceux stratifiés, non consolidés, riches en Fe, Mn et minéraux sulfurés, d'une puissance d'environ 10 m, est distribué sur une superficie de 5 km par 13 km, entre 2000 et 2200 m de profondeur au-dessous de la surface de la mer. Il contient plus de 32 millions de tonnes de métaux, y compris 0,4 Mt ou 1,3 % de Cu (en poids sec), 1,7 Mt ou 3,4 % de Zn, 0,1 % de Pb, 29 % de Fe, 54 ppm ou 5 000 tonnes d'Ag, 0,5 ppm d'Au et un peu de cobalt.

Dans l'océan Indien, les venues minéralisées sont principalement composées de sédiments métallifères et de stockwerks sulfurés. Les sédiments métallifères de type hydrothermal, associés aux laves basaltiques dans la vallée médiane du golfe d'Aden, sont composés d'endruits spongieux bruns ou d'endruits durs de couleur noire, avec oxydes de fer et de manganèse (jusqu'à 45 % de Mn), et de smectite massive verte et friable. On rencontre des venues similaires d'oxydes de Mn et Fe sur la crête de Carlsberg et la zone de fractures d'Owen. Les sédiments métallifères basaux d'âge Miocène moyen, épais d'environ 60 m, sont constitués de faciès zéolitiques et argileux à oxydes de Mn et Fe, passant à un faciès inférieur à oxydes de fer et de manganèse d'environ 5 m d'épaisseur qui repose sur des basaltes altérés du bassin de Wharton. Le faciès basal à oxydes de fer, d'une puissance de 2 m, est recouvert de boues calcaires d'âge Éocène, à l'emplacement de la crête Ninetyeast, et l'on rencontre des croûtes et sédiments riches en Mn et Fe dans d'autres sites. Les échantillons provenant des abords de l'intersection entre une vallée tectonique et la zone de fractures de Vitias contiennent des veines de minéraux sulfurés.

On rencontre dans tout l'océan Atlantique, dans les divers types de venues minérales décrites, des preuves abondantes de l'existence de processus effusifs hydrothermaux. Le long de la dorsale médio-Atlantique, et sur quelques guyots, s'est manifestée autrefois et récemment une activité hydrothermale. Un grand nombre des venues de sédiments métallifères basaux à proximité des marges continentales se sont formées durant les premiers stades de développement de la dorsale. Il semble aussi que l'existence de vastes nappes de nodules de manganèse soit liée à des effusions hydrothermales survenant le long des fossés tectoniques.

En Islande, l'activité hydrothermale est étroitement associée au volcanisme le long d'un segment de la dorsale médio-Atlantique (Mid-Atlantic Ridge, MAR), et représente une importante source d'énergie depuis de nombreuses années. Dans la région des crêtes bordant la vallée médiane de la dorsale médio-Atlantique, les sédiments métallifères et ferrifères

ganese crusts were dredged along the eastern flank of the central rift valley.

Metalliferous sediment from the Famous Area south of the Azores Fracture Zone along Transform Fault "A" is associated with manganese nodules and consists of dark brown Fe-Mn crusts and smectite clay rich in Fe and SiO_2. The smectite mud, believed to be hydrothermal, contains up to 45 % SiO_2 , 45% ferrous iron, and 2.5% Mn. Basalts in the Famous Area of MAR containing sulphide globules have special metallogenetic significance.

The TAG Hydrothermal field situated between the Atlantis and Kane fracture zones on the east wall of the Mid-Atlantic Ridge at water depths of 2000 to 4000 m covers an area of at least 100 km^2. Fault blocks in the topographically high area are intersected by closely spaced transform faults and linear normal faults. The mineralogy of the basalts indicates extensive metamorphism in the low temperature zeolite facies. Manganese oxide crusts containing 40 % Mn and high concentrations of ferride elements cover a tenth of the seafloor and are being precipitated at the rate of 2 cm per million years. Manganese oxide crusts and smectite muds have been sampled in many parts of the field and veins of iron oxide, talc, chlorite and zeolite cut the greenstone and metabasalt in the vicinity of transform faults.

The Snake Pit hydrothermal area about 25 km south of the Kane Fracture Zone covers 40 000 m^2 on the western part of a small terrace near the crest of the Median Valley. It is part of an active hydrothermal field located on a 10 km segment of the east wall of the rift valley where the ridge is spreading at the rate of 2 to 3 cm in 10 years and the valley narrows to 3 km from about 6 km. Deposits consisting of alternating hard and soft layers of Fe, Cu and Zn sulphide minerals disseminated in a clay matrix and lenses of massive sulphide were drilled in an area between the axis and east wall of the rift valley at a water depth of 3600 m where numerous black smokers are associated with a unique biological community. A linear zone higher on the east wall of the ridge has layered deposits of manganese and iron oxide, iron hydroxide, and iron silicate that contain high concentrations of other metals and helium.

Compound mounds at water depths of 3620 to 3675 m, with concentric inner and outer parts that are elliptical in plan view and 250 to 580 m wide, were explored in this hydrothermal field. The seafloor surrounding the mounds is covered by angular cobble to boulder size fragments of talus consisting of pillows of basalt and tan to red mottled metalliferous sediment that changes from red at the margins of the inner mound to black adjacent to the black smokers where euhedral pyrite crystals exhibit spectacular glitter. Hydrothermal precipitates dredged from the inner mound consisted of

(14 %) sont enrichis en As et Hg, et contiennent des quantités accessoires de Mn, Cu, Cr, Ni, Pb, B, Cd, et V dans les grains amorphes d'oxydes de fer. On rencontre des sédiments ferrugineux dans la région des chaînons Est et Ouest, et l'on a remonté par dragage des croûtes de manganèse le long du versant est de la vallée centrale du fossé tectonique (rift).

Les sédiments métallifères provenant de la région de Famous, au sud de la zone de fractures des Açores, le long de la faille transformante "A", sont associés à des nodules de manganèse, et sont composés de croûtes de Fe-Mn brun sombre, et d'argiles de type smectite riches en Fe et Si. Les boues à smectite, qui seraient d'origine hydrothermale, contiennent jusqu'à 45 % de Si, 45 % de fer ferreux, et 2,5 % de Mn. Les basaltes de la région de Famous sur la dorsale médio-Atlantique (MAR), qui contiennent des globules de minéraux sulfurés, ont une grande importance d'un point de vue métallogénique.

Le champ hydrothermal TAC situé entre les zones de fractures d'Atlantis et de Kane, le long de la paroi est de la dorsale médio-Atlantique entre 2000 et 4000 m de profondeur au-dessous du niveau de la mer, recouvre une superficie d'au moins 100 km^2. Des blocs faillés de la zone de topographie élevée sont recoupés par des failles transformantes très rapprochées et des failles normales linéaires. La minéralogie des basaltes indique qu'il y a eu un important métamorphisme dans le faciès zéolitique, caractérisé par une basse température. Des croûtes d'oxydes de manganèse contenant 40 % de Mn et de fortes concentrations de ferrides couvrent un dixième du fond marin, et précipitent à la vitesse de 2 cm par million d'années. Dans de nombreuses parties du champ, on a prélevé des échantillons de croûtes d'oxydes de manganèse et de boues à smectite; des veines d'oxydes de fer, de talc, de chlorite et de zéolite recoupent les roches vertes et les métabasaltes à proximités des failles transformantes.

La zone hydrothermale de Snake Pit, à environ 25 km au sud du la zone de fractures de Kane, couvre 40 000 m^2 de la partie ouest d'une petite terrasse située à proximité de la crête de la vallée médiane. Cette zone fait partie d'un champ hydrothermal actif situé le long d'un segment de 10 km de la paroi est de la vallée tectonique, où la dorsale se sépare à la vitesse de 2 à 3 cm tous les 10 ans, et où la vallée qui normalement a environ 6 km de large, se rétrécit à 3 km. On a effectué des forages dans des dépôts composés de couches dures et tendres alternées de minéraux sulfurés contenant Fe, Cu et Zn et disséminés dans une matrice argileuse, et de lentilles de sulfures massifs, dans une région située entre l'axe et la paroi est de la vallée tectonique, à 3 600 m de profondeur au-dessous de la surface de la mer, là où de nombreux "fumeurs" noirs sont associés à une communauté biologique exceptionnelle. Une zone linéaire située plus haut sur la paroi est de la crête contient des dépôts stratifiés d'oxydes de manganèse et de fer, d'hydroxydes de fer et de silicates de fer, contenant des concentrations élevées d'autres métaux et d'hélium.

Entre 3 620 m et 3 675 m de profondeur, des monticules composés, qui sont caractérisés par des structures concentriques intérieures et extérieures elliptiques en plan, et ont de 250 à 580 m de large, ont été explorés dans ce champ hydrothermal. Le fond marin qui entoure les monticules est recouvert de matériaux allant de galets anguleux à des fragments de la taille d'un bloc, provenant d'éboulis de laves basaltiques en

spongy-textured yellow pyrite and black sphalerite containing 38 % Fe, 9 % Zn and 1% Cu. Fragments, probably of stacks and chimneys, with chalcopyrite and pyrite on the concave side and sphalerite on the convex side have reddish-brown oxidized crusts several millimetres thick, and some fragments have manganese and iron oxide coatings 1 cm thick that contain 22 to 30% copper and up to 3% Zn. Estimates indicate that the mound deposit may contain 4.5 million tonnes of hydrothermal material. More than 35 inactive chimneys up to 5 m high, composed of sulphide minerals, mark a site of recent hydrothermal venting in an area 2 km northeast of the mound at water depths of 3500 to 3600 m.

Seven active hydrothermal sites with venting of hot water were found along the east wall of a section of the Mid-Atlantic Ridge between 11 and 26°N. Samples from the north wall of the Vema Fracture Zone show stockworks of copper-iron sulphides, chalcopyrite, pyrrhotite and pyrite associated with iron oxide, hydrated copper chloride and copper-iron oxide. Manganese crusts were sampled at a number of sites along the Vema Fracture Zone and samples of basalt and metagabbro are highly altered and metamorphosed.

Basal metalliferous sediment was intersected in some holes drilled in the northeast Atlantic Ocean at various distances between the continental margin and the Mid-Atlantic Ridge. The hydrothermal sediment varied from thin layered iron and manganese oxide to red, green and brown siliceous clay and chert containing trace amounts of minor elements. Most sections of this sediment are a few metres or less in thickness and the Fe and Mn content is less than 20% but deposits of red, green to brown clay up to 200 m thick cover diapiric structures north of the Cape Verde Islands. They probably mark the margins of basins where more extensive metalliferous sediment was deposited during early stages of ridge development.

Metalliferous sediment consisting of brown mud and manganese nodules in brown clay was recovered from Sommet Seamount and Fe and Mn rich sediment interbedded with calcareous brown ooze, montmorillonite clay, manganese nodules and volcano-clastic detritus in the caldera of Madcap Volcano indicate extensive hydrothermal effusive activity in the past between Africa and the Mid Atlantic Ridge.

Basal metalliferous sediment was also found in the North Atlantic in the southern part of the Labrador Sea. San Pablo Seamount, near the continental margin in the northwest Atlantic, is covered from water depths of 878 to 5300 m with hard layered manganese-iron oxide sediment about 30 cm thick that was deposited directly on lava flows.

coussins et de sédiments métallifères de couleur brun jaunâtre ou tachetés de rouge, qui de rouges sur les bords du monticule intérieur deviennent noirs à proximité des fumeurs noirs où les cristaux automorphes de pyrite ont un éclat spectaculaire. Les précipités hydrothermaux prélevés par dragage à l'intérieur du monticule étaient composés de pyrite jaune et de sphalérite noire spongieuses contenant 38 % de Fe, 9 % de Zn et 1 % de Cu. Des fragments, probablement issus d'évents et cheminées, et contenant de la chalcopyrite sur leur paroi concave et de la sphalérite sur leur paroi convexe, portent des croûtes oxydées brun rougeâtre de plusieurs millimètres d'épaisseur; certains sont recouverts d'endruits d'oxydes de fer et de manganèse de 1 cm d'épaisseur, contenant 22 à 30 % de Cu jusqu'à 3 % de Zn. Les calculs indiquent que les gisements associés aux monticules pourraient contenir 4,5 millions de tonnes de produits hydrothermaux. Plus de 35 cheminées inactives pouvant atteindre 5 m de haut, et composées de minéraux sulfurées, indiquent le site d'une activité hydrothermale effusive récente dans une région située à 2 km au nord-est des monticules, entre 3 500 et 3 600 m de profondeur au-dessous de la surface de la mer.

On a découvert sept sites hydrothermaux actifs libérant de l'eau chaude, le long de la paroi est d'une portion de la dorsale médio-Atlantique entre 11 et 26°N. Des échantillons provenant de la paroi nord de la zone de fractures de Vema indiquent l'existence de stockwerks composés de sulfures de cuivre et fer, de chalcopyrite, de pyrrhotine et de pyrite auxquels sont associés des oxydes de fer, des chlorures de cuivre hydratés et des oxydes de cuivre de fer. On a effectué des échantillonnages des croûtes de manganèse dans un certain nombre de sites bordant la zone de fractures de Vema; les échantillons recueillis de basaltes et de métagabbros sont fortement altérés et métamorphisés.

Quelques forages effectués dans le nord-est de l'Atlantique à diverses distances entre la marge continentale et la dorsale médio-Atlantique, ont recoupé un sédiment basal métallifère. La composition du sédiment d'origine hydrothermale variait d'oxydes de fer et de manganèse finement stratifiés, à des argiles siliceuses et cherts rouges, verts et bruns, contenant des quantités minimes d'éléments traces. La plupart des tranches de ce sédiment ont au plus quelques mètres d'épaisseur, et leur teneur en Fe et Mn représente moins de 20 %, mais des dépôts d'argiles rouges, vertes ou brunes atteignant 200 m d'épaisseur recouvrent des structures diapiriques au nord des îles du Cap Vert. Ils délimitent probablement les marges des bassins où se sont accumulés des sédiments métallifères plus vastes durant les stades initiaux de la formation d'une dorsale.

On a prélevé sur le guyot Sommet des sédiments métallifères composés de boues brunes et de nodules de manganèse inclus dans de l'argile brune; des sédiments riches en Fe et Mn, interstratifiés avec des vases calcaires brunes, de l'argile montmorillonitique, des nodules de manganèse et des roches détritiques volcano-clastiques présents dans la caldeira du volcan Madcap, indiquent qu'autrefois, a eu lieu une importante activité hydrothermale de type effusif entre l'Afrique et la dorsale médio-Atlantique.

On a aussi rencontré un sédiment basal métallifère dans l'Atlantique du Nord dans la partie sud de la mer du Labra-

Iron-manganese ratios in the sediment are about one and the Co content is up to 0.3%, Ni 0.25 %, Cu 0.09 % and Zn about 0.09 %.

Eocene or younger cherty sediment in a large area on the east side of the Bermuda Rise is interlayered in thick sections of basal sediment composed of banded olive grey to dark green clay, yellow to red-brown ferruginous sediment and manganese concretions. This section of sediment is overlain by extensive beds of chalk and calcareous ooze. One section of chert-ooze up to 90 m thick is associated with the olive-grey and red-brown sediment and the underlying basalt is altered to chlorite and cut by hydrothermal veins.

Brown metalliferous sediment composed of amorphous iron and manganese oxide with a high content of Co, Ni, Cu, and Zn was recovered from the summit of a seamount in the Guinea Basin. Angular blocks of basalt containing stockworks of iron and copper sulphide, iron oxide and clay indicate hydrothermal activity near the intersection of the Romanche offset and an axial segment of the Mid Atlantic Ridge. Orange to brown marl, iron and manganese crusts, and brown calcareous clay occur above and below the Pleistocene-Holocene boundary in the equatorial area between the Amazon River delta and the Romanche Offset. Basal metalliferous sediment was intersected in a series of drillholes marking a section from the Mid-Atlantic Ridge westward along the Rio Grande Rise. The core samples show that the iron and manganese sediment distal from the ridge crest is relatively rich in Fe, Mn, and P, and poor in Si, Al and Ti and that submarine volcanism has been a source of metals in the sediment since Eocene or Late Cretaceous time.

In the South Pacific, basal metalliferous sediment in the Peru Basin between the Galapagos Rise and the continental margin contains up to 30 % Fe, 15 % Mn, 20 % SiO_2 and is enriched in Cu, Ni, Cr, and Zn.

Metalliferous sediment rich in Fe and Mn has been sampled over the large basin known as the Bauer Deep situated between the East Pacific Rise and the Galapagos Rise. It is more than 9 m thick in some places and composed of amorphous and crystalline iron and manganese oxide in colloidal size particles, micronodules and iron-rich montmorillonite clay. The composition of the sediment varies greatly and the content of Fe ranges from 10 to 25 %, Mn from 3 to 6 %, Mg and Ca from 1 to 2 %, Na and K from 1 to 2 %, Al from 2 to 3 % , SiO_2 from 30 to 50 %, and Ba from 1 to 2 %. Most of the sediment is enriched in Ni, Cu, Zn, Co, Cr, Sr, B, Ba and other metals. The minor elements are believed to be adsorbed on the colloidal particles of iron and manganese oxide and absorbed in the smectite clay. Accumulation rates for the Bauer

dor. Le guyot de San Pablo, proche de la marge continentale dans le nord-ouest de l'Atlantique, est recouvert entre 878 m et 5 300 m de profondeur au-dessous de la surface de la mer, d'une couche stratifiée et dure de sédiments composés d'oxydes de manganèse et de fer, d'environ 30 cm d'épaisseur, qui se sont directement déposés sur les coulées de lave. Dans le sédiment, le rapport fer-manganèse est d'environ un, et la teneur en cobalt atteint 0,3 %, la teneur en Ni 0,25 %, la teneur en Cu 0,09 % et la teneur en Zn environ 0,09 %.

Dans une vaste région, sur le versant est du seuil des Bermudes, des sédiments siliceux (cherts) de l'Éocène ou plus récents forment des intercalations dans d'épaisses sections d'un sédiment basal composé d'argiles rubanées de couleur gris olive à vert sombre, de sédiments ferrugineux jaunes à brun rouge, et de concrétions de manganèse. Cette tranche sédimentaire est recouverte de vastes lits de craie et de boues calcaires. Une tranche de vases et roches siliceuses (cherts) atteignant 90 m d'épaisseur est associée aux sédiments gris olive et brun rouge, et le basalte sous-jacent est altéré en chlorite, et recoupé par des veines hydrothermales.

Le sédiment métallifère brun composé d'oxydes amorphes de fer et de manganèse contenant des concentrations élevées de Co, Ni, Cu et Zn a été prélevé au sommet d'un guyot située dans le bassin de Guinée. Des blocs basaltiques anguleux contiennent des stockwerks composés de sulfures de fer et de cuivre, et des oxydes de fer et argiles indiquent l'existence d'une activité hydrothermale près de l'intersection de la faille transformante de Romanche et d'un segment axial de la dorsale médio-Atlantique. On rencontre au-dessus et au-dessous de la limite entre le Pléistocène et l'Holocène, dans la région équatoriale, entre le delta de l'Amazone et la faille transformante de Romanche, des marnes oranges à brunes, des croûtes de fer et de manganèse, et des argiles calcaires brunes. Une série de forages ont recoupé un sédiment basal métallifère, suivant une ligne partant de la dorsale médio-Atlantique, en direction de l'ouest, le long du seuil du Rio Grande. Les carottes d'échantillonnage montrent que les sédiments ferrifères et manganésifères distaux par rapport à la crête de la dorsale sont relativement riches en Fe, Mn et P, et pauvres en Si, Al et Ti, et que le volcanisme sous-marin introduit des métaux dans le sédiment depuis l'Éocène ou le Crétacé supérieur.

Dans le Pacifique du Sud, le sédiment métallifère basal qui se trouve dans le bassin du Pérou entre la crête des Galapagos et la marge continentale contient jusqu'à 30 % de Fe, 15 % de Mn, 20 % de Si, et est enrichi en Cu, Ni, Cr et Zn.

On a prélevé des échantillons de sédiment métallifère riche en Fe et Mn dans le vaste bassin connu sous le nom de fosse abyssale de Bauer, et situé entre la dorsale du Pacifique de l'Est et la crête des Galapagos. Ce sédiment a plus de 9 m d'épaisseur localement, et il est composé d'oxydes amorphes ou cristallins de fer et de manganèse présents dans des particules de dimensions colloïdales, dans des micronodules et dans des argiles montmorillonitiques ferrifères. La composition du sédiment varie grandement, et sa teneur en Fe est comprise entre 10 et 25 %, sa teneur en Mn entre 3 et 6 %, en Mg et Ca entre 1 et 2 %, en Na et K entre 1 et 2 %, en Al entre 2 et 3 %, en SiO_2 entre 30 et 50 %, et en Ba entre 1 et 2 %. En majeure partie, ce sédiment est enrichi en Ni, Cu, Zn, Co, Cr, Sr, B, Ba

Deep sediments are about 2.5 mm/1000 a, and their bulk composition and the distribution patterns of minor constituents leave little doubt that they are modern sedimentary progenitors of oxide facies iron-formation. Seamounts in the basin are covered by similar metalliferous sediment. Siliceous metalliferous sediments with variable amounts of Fe and Mn and enriched in Cu, Ni, Zn and other metals are distributed throughout the Central Basin south of the Bauer Deep.

Siliceous metalliferous sediments composed of iron and manganese oxide and nontronite clay are associated with active and recent hydrothermal vent sites along the axis and flanks of the southern part of the East Pacific Rise. Reports indicate that they are enriched in ferride and nonferrous metals, and some have anomalous amounts of U, Th and REE. Helium-rich plumes traced 200 km westward from the axial area of the ridge at 15°S mark the location of a very large hydrothermal field. Deep grabens, recent faulting, and intense hydrothermal activity are developed along the crest of the ridge from 17 to 22°S and Fe , Cu and Zn sulphide has been deposited in the graben basins. Iron and manganese oxide sediments, accumulating rapidly along the western flank of the ridge, are enriched in P, La. V, Y, Rb, and other minor elements commonly found in hydrothermal sediments. Spreading of the ridge is taking place at the rate of 16 cm/a in this area. A traverse across the ridge shows that the calcareous metalliferous ooze on the east flank of the ridge has a lower content of Fe, Mn, Cu and Zn than the iron-manganese marls on the west flank which are being deposited 2 to 10 times more rapidly. Fe:Mn ratios are higher in the ridge crest area than on the flanks and Si to Al ratios are much higher on the crest and western flank indicating westward dispersion of silica. A composite sample from a southern graben composed of pyrite, marcasite, chalcopyrite, and sphalerite contains 35 % Fe, 9 % Zn, 6.8 % Cu, and 45.5 % S.

A basal iron and manganese oxide facies may extend over the Central East Pacific Basin. The amorphous iron oxide sediment interbedded with siliceous radiolarian ooze overlying basalt that was sampled at two Deep Sea Drilling Program sites may be related to metalliferous sediment on the west flank of the East Pacific Rise. Metalliferous sediments in the Tiki Basin situated between the Marquesas and the Tuamotu fracture zones and the Tuamotu Archipelago are associated with calcareous ooze, red pelagic clay and micronodules of Fe and Mn. They are composed of iron hydroxide minerals and smectite clay and are similar in composition to the Bauer Deep hydrothermal sediment. Similar metalliferous sediments from north of the Marquesas Fracture Zone and west of the

et en autres métaux. On estime que les éléments traces ont été absorbés par les particules colloïdales d'oxydes de fer et de manganèse et par les argiles smectiques. Dans la fosse abyssale de Bauer, les sédiments s'accumulent à la vitesse d'environ 2,5 mm/1000 ans; leur composition globale et les modes de distribution des éléments traces laissent subsister peu de doute sur le fait que ces sédiments représentent la phase préliminaire actuelle d'une formation ferrifère à faciès oxydé. Les guyots situés dans le bassin sont recouverts de sédiments métallifères de même type. Dans tout le Bassin central, au sud de la fosse abyssale de Bauer, sont distribués des sédiments métallifères siliceux caractérisés par des quantités variables de Fe et Mn et enrichis en Cu, Ni, Zn et en autres métaux.

Les sédiments métallifères siliceux composés d'oxydes de fer et de manganèse et d'argiles de type nontronite sont associés à des sites d'activité hydrothermale effusive, active et récente, le long de l'axe et des flancs de la partie sud de la dorsale du Pacifique de l'Est. Des rapports indiquent qu'ils sont enrichis en métaux non ferreux et en ferrides, et que certains contiennent des concentrations anormales de U, Th, et de terres rares. Les panaches riches en hélium, repérés à 200 km à l'ouest à partir de la région axiale de la dorsale, à 15°S, signalent l'emplacement d'un champ hydrothermal très vaste. De profonds grabens, des failles récentes et une activité hydrothermale intense sont apparus le long de la crête de la dorsale entre 17° et 22°S; des sulfures de Fe de Cu et de zinc se sont déposés dans les bassins de type graben. Les sédiments contenant des oxydes de fer et de manganèse, qui se sont rapidement accumulés le long du flanc occidental de la dorsale, sont enrichis en P, La, V, Y, Rb et en autres éléments traces que l'on rencontre souvent dans les sédiments de type hydrothermal. La séparation de la dorsale a lieu à la vitesse de 16 cm par an dans cette région. Une ligne transversale suivie durant l'exploration de la dorsale montre que les boues calcaires métallifères situées sur le flanc est de la dorsale sont caractérisées par une teneur plus faible en Fe, Mn, Cu et Zn que les marnes à la fois ferrifères et manganésifères situées sur le flanc ouest, qui se déposent 2 à 10 fois plus rapidement. Les rapports Fe/Mn sont plus élevés dans la région de la crête de la dorsale que sur les versants de celle-ci, et les rapports Si/Al sont beaucoup plus élevés sur la crête et sur le flanc occidental, ce qui indique une dispersion de la silice vers l'ouest. Un échantillon composite provenant d'un graben situé au sud, était composé de pyrite, de marcassite, de chalcopyrite et de sphalérite et contenait 35 % de Fe, 9 % de Zn, 6,8 % de Cu et 45,5 % de S.

Il est possible qu'un faciès basal à oxydes de fer et de manganèse occupe toute l'étendue du bassin central du Pacifique de l'Est. Les sédiments à oxydes de fer amorphes, interstratifiés avec des boues siliceuses à radiolaires recouvrant le basalte, ont fait l'objet d'un échantillonnage en deux sites du Programme de forage à grande profondeur au-dessous de la surface de l'océan; il est possible qu'ils soient apparentés à des sédiments métallifères rencontrés sur le flanc ouest de la dorsale du Pacifique de l'Est. Les sédiments métallifères du bassin de Tiki situé entre les îles Marquises et les zones de fractures et l'archipel des Touamotou sont associés à des boues calcaires, à des argiles pélagiques rouges et à des micronodules de Fe et Mn. Ces sédiments sont composés de minéraux à base d'hydroxydes de fer et de smectites, et ont une composition

Marquesas Islands and from the Tuamotu Archipelago are rich in Fe, Mn, Si, Al, and Ti.

Several sites marginal to the southwest part of the Pacific Plate on the crest of small axial volcanoes inside the rift valley of a spreading centre in the Manus back-arc basin east of New Guinea have clay patches and broken chimneys and mounds probably composed of sulphide minerals that were formed by the wasting of chimneys. Dark brown clay sediments and manganese nodules cover a large area of seabed to the southwest of these sites. Calcareous oozes are predominant on the seabed to the northwest, and siliceous oozes to the northeast, of Western Samoa. Manganese nodules are not abundant, but brown muds are widespread and manganese and iron oxide crusts coat pebbles and volcanic rock at a number of sites.

The Lau and North Fiji basins are near a subduction zone where the Pacific Plate plunges beneath the Indo-Australian Plate. The Lau Basin trends northeast and extends along the Tonga Trough and Ridge. Fragments with concentric layers of sphalerite, chalcopyrite and pyrite and amorphous silica containing spheroids up to 5 mm are part of a broken chimney dredged from a rift valley on a spreading ridge in this basin. The spreading area extends north for 47 km and there is evidence of submarine "weathering" on the seafloor where the rocks are covered by manganese oxide and yellow clay sediment. Samples from a traverse across the Lau Basin showed high accumulation rates for Fe, Mn, Cu, Zn, and As close to the spreading ridge, which indicates a substantial input of metals from hydrothermal sources. The southern Lau Basin trends northeast and the Valu Fa Ridge extends northeast for 60 km along a spreading axis. Metalliferous sediment consisting of nontronite clay and manganese oxides with a high Mn/Fe ratio covers much of this area. Samples from seamounts along Valu Fa Ridge contain hydrothermal oxides, pyrite, chalcopyrite and opal, and are associated with andesite lava with a high content of Si, Fe and Ti.

Lavas in a narrow northeast-trending valley in the southern part of the North Fiji Basin are impregnated with hydrothermal sulphide. Braemar Ridge in the north of the basin has a heterogeneous suite of serpentinized dunite, dacite tuffs, volcanoclastic rocks, hydrothermal manganese crusts and pelagic carbonate rocks. In the northern part of the North Fiji Basin hydrothermal sulphide minerals impregnate volcanic rocks, and manganese and iron oxide and iron silicate minerals are found around active and fossil spreading zones and on seamounts. Thin-banded manganese oxide crusts along the Tonga-Kermadec Ridge containing 49 % Mn but very little Fe, are relatively rich in Li, Zn, Mo, and Cd. Cores from vent sites near two

semblable à celle des sédiments d'origine hydrothermale de la fosse abysalle de Bauer. Des sédiments métallifères similaires provenant du nord de la zone de fractures des Marquises, et de l'ouest des îles Marquises et de l'archipel des Touamotou, sont riches en Fe, Mn, Si, Al et Ti.

Plusieurs sites en marge de la partie sud-ouest de la plaque du Pacifique, sur la crête de petits volcans axiaux, dans la vallée tectonique d'un centre d'expansion situé dans le bassin de Manus, dans la concavité de l'arc insulaire à l'est de la Nouvelle-Guinée, sont caractérisés par l'existence de nappes argileuses et de cheminées et de monticules, ces derniers probablement formés par effondrement des cheminées composées de matériaux sulfurés. Les sédiments argileux brun sombre et les nodules de manganèse couvrent une vaste superficie du fond marin au sud-ouest de ces sites. Les boues calcaires sont dominantes sur le fond marin au nord-ouest et les boues siliceuses au nord-est de Samoa occidental. Les nodules de manganèse n'abondent pas, mais les boues brunes sont largement répandues, et les croûtes d'oxydes de fer et de manganèse forment un enduit sur les galets et sur la roche volcanique dans plusieurs sites.

Le bassin Lau et le bassin nord des Fiji se situent près d'une zone de subduction, où la plaque du Pacifique plonge au-dessous de la plaque indo-australienne. Le bassin de Lau a une direction générale nord-est et suit la fosse et la crête de Tonga. Les fragments caractérisés par des couches concentriques de sphalérite, de chalcopyrite et de pyrite, ainsi que de la silice amorphe contenant des sphéroïdes d'une taille maximale de 5 mm, font partie d'une cheminée fracturée; on a remonté ces fragments par dragage dans la vallée tectonique d'une dorsale en expansion présente dans ce bassin. La zone d'expansion s'étend au nord sur 47 km, et l'on a découvert des indices d'une "altération" sous-marine sur le fond marin, là où les roches sont recouvertes de sédiments composés d'oxydes de manganèse et d'argile jaune. Les échantillons provenant d'une ligne transversale suivant laquelle on a exploré le bassin de Lau, indiquaient de grandes vitesses d'accumulation dans le cas de Fe, Mn, Cu, Zn et As, à proximité de la dorsale, ce qui indique un apport substantiel de métaux par des sources hydrothermales. La partie sud du bassin de Lau a une orientation nord-est, et la crête de Valu Fa s'étend vers le nord-est sur 60 km le long d'un axe d'expansion. Des sédiments métallifères composés d'argile de type nontronite et d'oxydes de manganèse, avec un rapport élevé Mn/Fe, recouvrent une grande partie de cette région. Des échantillons prélevés dans des guyots, le long de la crête de Valu Fa, contiennent des oxydes, de la pyrite, de la chalcopyrite et de l'opale d'origine hydrothermale, produits associés à des laves andésitiques caractérisées par une teneur élevée en Si, Fe et Ti.

Les laves situées dans une étroite vallée d'orientation nord-est, dans la partie sud du bassin nord des Fiji, sont imprégnées des sulfures hydrothermaux. La crête de Braemar, dans le nord de bassin, est caractérisée par une série hétérogène de dunites serpentinisées, de tufs dacitiques, de roches volcanoclastiques, de croûtes hydrothermales de manganèse et de roches carbonatées d'origine pélagique. Dans la partie nord du bassin nord des Fiji, des minéraux sulfurés hydrothermaux imprègnent les roches volcaniques, et l'on trouve des oxydes de manganèse et de fer et des minéraux ferrosilicatés aux alentours de zones

active volcanoes off the Island of Epi in the eastern part of the New Hebrides Arc are composed of red silty beds, amorphous iron oxide (27 %) and polymetallic sulphide.

Iron-rich sediments on the outer continental shelf of northern New South Wales, Australia, are enriched in Fe, Mn, P, and As. The authigenic mineral phase is chamosite rather than glauconite. The nodules are enriched in Fe, P, and As and the phosphate in them may have come from the iron-rich sediments. Significant phosphate released during the reduction of the iron-rich sediments has been precipitated as carbonate-fluorapatite. The authigenic sediment contains 18 to 34 % SiO_2, 6 to 9 % Al_2O_3, 28 to 41 % FeO and 0.1 to 1.6 P_2O_5 and high amounts of Mn, As, and Zn.

Basal metalliferous sediment of Eocene age was cored on the outer arch of the Philippine Trench in the Northwest Pacific. Metalliferous sediment from the West Philippine Basin from areas northeast and southwest of the Philippine Trench consists of Eocene brown layered ferruginous clay up to 158 m thick, that rests directly on basalt. Sedimentation rates are 2-3 mm/Ma and the brown clay contains 62 % SiO2, 44 % Fe, 9 % Mn and high amounts of Cu, Ni, Co, Zn and REE. This may be the thickest section of recent iron-formation protosediment known.

High geothermal gradients were found in the Mariana Trough and high methane and helium anomalies were recorded in the adjacent Mariana Back-Arc Basin. Mounds of sediment in the trough are up to 1000 m in diameter and 100 m high, and consist of ferruginous hydrothermal sediment capped by brownish-black manganese crusts, spires and knobs. Siliceous ferruginous sediment up to 5 m thick is widely distributed in depressions in the trough and back-arc basin.

Manganese-iron oxide crusts rich in cobalt related to Mid-Cretaceous basaltic volcanism are widespread on seamounts in the Line Islands Ridge and Mid Pacific Mountains areas. The crusts are composed of manganese oxide minerals and amorphous iron hydroxide and contain 13 to 16 % Fe, 18 to 29 % Mn, 0.6 to 1.38 % Co, 0.2 to 0.6 % Ni, 0.03 to 0.15 % Cu, 0.3 to 0.8 % P_2O_5, 1 to 1.7 % Ti, and many other minor elements. Metalliferous sediment occurs in thick sections of radiolarian ooze, chert and dark brown sediment containing iron-manganese micronodules in the equatorial area at 166°W. Samples from the crater of Loihi Seamount, Hawaii are rich in goethite and nontronite and enriched in Mn, Cu, Ni, Pb, Cd, As, and Hg.

Siliceous iron- and manganese- rich basal metalliferous sediment has been sampled over a large equatorial area from about 105 to 135°W. Siliceous

d'expansion actives ou fossiles, et sur les guyots. Les croûtes d'oxydes de manganèse finement rubanées, situées le long de la crête de Tonga-Kermadec, et contenant 49 % de Mn mais très peu de Fe, sont relativement riches en Li, Zn, Mo et Cd. Les carottes d'échantillonnage prélevées dans des sites d'évents proches de deux volcans actifs au large de l'île Épi, dans la partie est de l'arc des Nouvelles-Hébrides, sont composées de strates limoneuses rouges, d'oxydes de fer amorphes (27 %) et de sulfures polymétalliques.

Les sédiments ferrifères de la plate-forme continentale extérieure du nord de la Nouvelle-Galles du Sud en Australie, sont enrichis en Fe, Mn, P et As. La phase minérale authigène est la chamosite plutôt que la glauconite. Les nodules sont enrichis en Fe, P et As, et les phosphates qu'ils contiennent proviennent peut-être des sédiments ferrifères. Des quantités appréciables de phosphates libérés durant la réduction des sédiments ferrifères ont précipité sous forme de fluorapatite carbonatée. Le sédiment authigène contient 18 à 34 % de SiO_2, 6 à 9 % d'Al_2O_3, 28 à 41 % de FeO et 0,1 à 1,6 % de P_2O_5, et des concentrations élevées de Mn, As et Zn.

On a prélevé des carottes d'échantillonnage dans un sédiment métallifères basal d'âge Éocène, sur l'arc extérieur de la fosse des Philippines, dans le nord-ouest du Pacifique. Les sédiments métallifères du bassin ouest des Philippines, entre des zones du nord-ouest et du sud-ouest de la fosse des Philippines, sont constituées d'argiles stratifiées brunes et ferrugineuses, d'âge Éocène, d'épaisseur maximale 158 m, qui reposent directement sur les basaltes. Les taux de sédimentation sont de 2 à 3 mm/Ma, et les argiles brunes contiennent 62 % de SiO_2, 44 % de Fe, 9 % de Mn, et des concentrations élevées de Cu, Ni, Co, Zn et de terres rares. Ceci pourrait représenter la plus épaisse tranche connu de protosédiments ferrifères récents.

On a mesuré dans la fosse des Mariannes des gradients géothermiques élevés, et enregistré des anomalies élevées en méthane et en hélium dans le bassin adjacent situé dans la convexité de l'arc des Mariannes. Dans cette fosse, des monticules de sédiments ferrugineux hydrothermaux couverts à leur sommet de croûtes, flèches et bosses constituées de manganèse noir brunâtre, atteignant parfois 1 000 m de diamètre et 100 m de hauteur. Des sédiments siliceux et ferrugineux d'une puissance de 5 m largement distribués dans des dépressions de la fosse et du bassin de la convexité de l'arc insulaire.

Des croûtes d'oxydes de fer et de manganèse, enrichies en cobalt par le volcanisme basaltique du Crétacé moyen, apparaissent souvent sur les guyots, dans la région de la crête des îles de la Ligne et des monts médio-Pacifique. Les croûtes minéralisées sont composées d'oxydes de manganèse et d'hydroxyde de fer amorphe, et contiennent 13 à 16 % de Fe; 18 à 29 % de Mn; 0,6 à 1,38 % de Co; 0,2 à 0,6 % de Ni; 0,03 à 0,15 % de Cu; 0,3 à 0,8 % de P_2O_5; 1 à 1,7 % de Ti; et un grand nombre d'autres éléments traces. On rencontre des sédiments métallifères dans d'épaisses tranches de boues à radiolaires, de cherts et de sédiments brun sombre contenant des micronodules de fer et de manganèse au niveau de la zone équatoriale à 166°W. Des échantillons recueillis dans le cratère du guyot Loihi à Hawaii sont riches en goethite et en nontronite, et enrichis en Mn, Cu, Ni, Pb, Cd, As et Hg.

metalliferous sediment such as that at the Dome Site C between the Clarion and Clipperton fracture zones is typical of sediment in a large area. It is composed of iron and manganese oxide and nontronite clay and enriched in a large number of the minor metals. Basal hydrothermal sediment at MANOP Site M, 25 km east of the East Pacific Rise, is 500 000 years old, rich in Fe and Mn, and has Fe/Mn ratios of 2.6 to 2.9.

Galapagos Ridge extends eastward from its intersection with the East Pacific Rise at 2°N and has developed during spreading of the Nazca Plate to the south from the Cocos Plate to the north at an average rate of 7 cm/a over the last 3 Ma. Extensive deposits of polymetallic sulphide and yellow-brown ocherous sediment have been explored at 86°W in hydrothermal fields along the rift valley walls in the axial zone of a segment of the ridge 30 km long. The largest sulphide deposit, consisting of a mass of coalesced chimneys and stacks, is about 35 m high, 20 to 200 m wide and 1000 m long and is composed of pyrite, chalcopyrite, sphalerite, amorphous silica, and clay. Seven samples have an average content of 40 % S, 38 % Fe, 6.5 % Cu, 7 % SiO_2, 1 % Zn, 0.5 % Mn, 0.3 % Al_2O_3, 360 ppm Se, 250 ppm Co, 270 ppm Mg, 181 ppm Mo, 215 ppm Pb, 45 ppm As and Ba, and less than 40 ppm of Cd, Cr, P, Hg, Ni, Sn, V, U and W, and less than 0.2 ppm Au, 0.05 Pa and an average of 21 ppm Ag. Sulphide deposits are flanked by iron oxide sediment and manganese oxide crusts, which contain up to 2.3 % Zn and 0.5 % Cu and many domes and hummocks along the ridge axis are coated with orange iron oxide and amorphous silica and cut by veins of manganese oxide. Sediment 28 km north of the ridge axis consists of manganese crust and green nontronite clay. A 200 km^2 area from 17 to 30 km south of the ridge and extending parallel to it for 27 km has thousands of manganese rich-mounds developed along major fracture zones. The mounds are composed of manganese oxide and nontronite clay and contain 58 % MnO and significant amounts of trace elements. Manganese oxide crusts up to 6 cm thick were sampled on the northwest flank of the ridge.

Earthy brown hydrothermal sediment occurs on two seamounts symmetrically located 35 km to the east and west of the East Pacific Rise at 8°N, and ocherous iron and manganese oxide and sulphide fragments were dredged from the Clipperton Seamount northwest of this site. An active vent field along the east side of the rift valley at 11°N has mounds composed of sulphide rich in Fe, Zn, and Cu, and hydrothermal venting is taking place in a graben on the ridge at 11°30'N.

A segment of the East Pacific Rise north of 12°45'N has been explored along the axial graben for 20 km. Deposits of Fe, Cu and Zn sulphide are

On a prélevé des échantillons de sédiment métallifère basal siliceux enrichi en fer et en manganèse, sur une vaste zone du niveau de l'équateur, à peu près entre 105°W et 135°W. Les sédiments métallifères siliceux comme ceux que l'on rencontre sur le site C de Dome entre les zones de fractures de Clarion et de Clipperton, sont typiques des sédiments qui occupent une vaste région. Ils sont composés d'oxydes de fer et de manganèse et d'argiles de type nontronite, et enrichis en un grand nombre d'éléments traces métalliques. Le sédiment basal d'origine hydrothermale que l'on rencontre sur le site M de MANOP, à 25 km à l'est de la dorsale du Pacifique de l'Est, date de 500 000 années; il est enrichi en Fe et Mn, et se caractérise par un rapport Fe/Mn compris entre 2,6 et 2,9.

La crête des Galapagos se prolonge vers l'est, à partir de son intersection avec la dorsale du Pacifique de l'Est, à 2°N, et s'est formée durant l'expansion de la plaque de Nazca au sud, à partir de la plaque des Cocos au nord, à la vitesse de 7 cm par an, durant les trois derniers des Cocos au nord, à la vitesse de 7 cm par an, durant les trois derniers Ma. On a exploré de vastes dépôts de sulfures polymétalliques et de sédiments composés d'ocre brun jaunâtre, à 86°W, dans des champs hydrothermaux bordant les parois de la vallée tectonique dans la zone axiale d'un segment de la crête de 30 km de long. Le plus vaste gîte sulfuré, composé de cheminées et colonnes qui ont fusionné, a environ 35 m de haut, 20 à 200 m de large et 1000 m de long, et se compose de pyrite et de chalcopyrite, de sphalérite, de silice amorphe et d'argile. Sept échantillons ont une teneur moyenne de 40 % en S, 38 % en Fe, 6,5 % en Cu, 7 % en SiO_2, 1 % en Zn, 0,5 % en Mn, 0,3 % en Al_2O_3, 360 ppm en Se, 250 ppm en Co, 270 ppm en Mg, 181 ppm en Mo, 215 ppm en Pb, 45 ppm en As et Ba, et moins de 40 ppm en Cd, Cr, P, Hg, Ni, Sn, V, U et W, et de moins de 0,2 ppm en Au, 0,05 ppm en Pa, et en moyenne de 21 ppm en Ag. Les gîtes sulfurés sont bordés par des sédiments contenant des oxydes de fer et des croûtes d'oxydes de manganèse qui contiennent jusqu'à 2,3 % de Zn et 0,5 % de Cu; un grand nombre de dômes et de buttes situés le long de l'axe de la crête sont recouverts d'oxydes de fer de couleur orange et de silice amorphe, et recoupés par des veines d'oxydes de manganèse. A 28 km au nord de l'axe de la crête, les sédiments sont composés d'une croûte de manganèse et de nontronite verte. Une zone de 200 km^2, située entre 17 et 30 km au sud de cette crête, et disposée parallèlement à celle-ci sur 27 km, est caractérisée par la présence de milliers de monticules riches en manganèse, qui se sont formés le long des principales zones de fractures. Les monticules sont composés d'oxydes de manganèse et d'argile de type nontronite, et contiennent 58 % de MnO et des quantités notables d'éléments traces. On a procédé à des prélèvements de croûtes d'oxyde de manganèse atteignant parfois 6 cm d'épaisseur, sur le versant nord-ouest de la crête.

On rencontre des sédiments hydrothermaux de couleur brun terreux sur deux guyots, situés symétriquement à 35 km à l'est et à l'ouest de la dorsale du Pacifique de l'Est à 8°N, et l'on a ramené par dragage des oxydes de fer et de manganèse de couleur ocre et des fragments de sulfures du guyot Clipperton au nord-est de ce site. Un champ d'évents actifs longeant le versant est de la vallée tectonique à 11°N, comporte des monticules composés de sulfures enrichis en Fe, Zn et Cu, et l'on

associated with hydrothermal vents and distributed over a width of 200 m at intervals of 100 to 200 m along the ridge axis. Estimates indicate that more than 20 000 tonnes of sulphide minerals have accumulated in the chimneys, stacks and talus in the past 100 years. Seamounts east of this site on the ridge flank are 6 km in diameter and 400 m high. Extensive deposits of ocherous goethite and siliceous iron-copper sulphide and pyrite rich in Co cover the slopes and summit of the seamounts which may contain ten times more sulphide mineral than the deposits in the adjacent segment of the ridge. The ocherous limonite and goethite deposits are coated by scoria-like iron-manganese material. The Fe, Cu, and Zn sulphide deposits on the summit of one of the seamounts are about a metre thick and samples contain up to 31 % Cu, 41 % Zn, 45 % Fe, 47 % S, and significant enrichment of Pb, As, Ag, Se, Co, Ni, Cd, and Sr.

Sulphide deposits are distributed along the axial zone of the East Pacific Rise at 21°N between the Tamayo and Rivera transform fault zones. They consist of large conical and tubular structures of iron, copper and zinc sulphide, limonite, opaline silica, and iron-rich clay and zeolite. The ridge has been spreading at the rate of 3 cm/a over the past 4 Ma and the crestal area is dominated by volcanic hills. An area to the north, 7 km long and 100 m wide, on the west side of the ridge axis has rows of mounds up to 10 m high at intervals of 3 to 4 m, composed of iron, copper and zinc sulphide covered by red, white, and dark grey ochre. Mounds, chimney and vent structures up to 30 m high are associated with black and white plumes in an area to the south and are composed of polymetallic sulphide that is rich in zinc in the vicinity of the lower temperature hydrothermal vents (273°C) and rich in Cu around the higher temperature vents. Red Volcano and Green Volcano seamounts on the west flank of the ridge at 21°N have large deposits of metalliferous sediment. Copper-rich polymetallic sulphide facies blanketed by ocherous sediment are associated with hydrothermal venting in the caldera of these volcanoes.

The system of transform faults and axes of spreading extends north from the East Pacific Rise through the Gulf of California, continues along the San Andreas Fault on the continent and north on the seafloor as the Gorda and Juan de Fuca ridges. Separation of Baja California Peninsula from mainland Mexico on the margin of the Pacific and North American Plate is taking place at the rate of 3 to 6 cm/a. Basalt from sites at the mouth of the Gulf of California is interlayered with sediment and smectite muds and altered and veined by sulphide, carbonate, smectite clay and zeolite minerals.

The Guaymas Basin consists of two en echelon troughs 3 to 5 km wide and 20 km long situated on a fast-spreading segment of the rift-fault system.

a observé une activité effusive hydrothermale dans un graben à l'emplacement de la crête, à 11°30'N.

On a exploré un segment de la dorsale du Pacifique de l'Est, au nord de 12°45'N le long du graben axial, sur une distance de 20 km. Des gisements de sulfures de Fe, Cu et Zn sont associés aux évents hydrothermaux, et distribués sur une largeur de 200 m à des intervalles de 100 à 200 m le long de l'axe de la dorsale. D'après des estimations, plus de 20 000 tonnes de minéraux sulfurés se seraient accumulés dans les cheminées, colonnes et éboulis minéralisés au cours des 100 dernières années. Les guyots situés à l'est de ce site sur le flanc de la dorsale ont 6 km de diamètre et 400 m de haut. De vastes gisements de goethite de couleur ocre et de sulfures siliceux de fer et de cuivre, et de la pyrite riche en Co, recouvrent les versants et le sommet des guyots qui peuvent contenir dix fois plus de minéraux sulfurés que les gisements du segment adjacent de la dorsale. Les gisements de limonite ocre et de goethite sont recouverts d'un produit ferrifère et manganésifère semblable à des scories. Les gîtes sulfurés de Fe, cuivre et zinc situés au sommet de l'un des guyots ont environ 1 m d'épaisseur, et les échantillons recueillis contiennent jusqu'à 31 % de Cu, 41 % de Zn, 45 % de Fe, 47 % de S, et montrent un enrichissement significatif en Pb, As, Ag, Se, Co, Ni, Cd et Sr.

Les gîtes sulfurés se répartissent suivant la zone axiale de la dorsale du Pacifique de l'Est, à 21°N, entre les zones de failles transformantes de Tamayo et de Rivera. Ils sont constitués de grandes structures coniques et tubulaires composées de sulfures de fer, cuivre et zinc, de limonite, de silice opaline, et d'argile ferrifère et de zéolites. A l'emplacement de la dorsale, l'expansion de la croûte terrestre s'effectue à la vitesse de 3 cm par an depuis quatre Ma, et la crête de la dorsale est dominée par des collines volcaniques. Une zone située au nord, de 7 km de long et de 100 m de large, du côté ouest de l'axe de la dorsale, comporte des rangées de monticules atteignant 10 m de haut et séparées par des intervalles de 3 à 4 m; ceux-ci sont composés de sulfures de fer, cuivre et zinc recouverts d'ocre rouge, blanche et gris sombre. Les monticules, cheminées et évents qui atteignent parfois 30 m de haut, sont associés à des panaches noirs et blancs dans une zone située au sud, et sont composés de sulfures polymétalliques enrichis en zinc à proximité des évents hydrothermaux de relativement basse température (273°C), et enrichis en Cu autour des évents de température plus élevée. Les guyots Red Volcano et Green Volcano formés sur le flanc ouest de la dorsale à 21°N, comportent de vastes dépôts de sédiments métallifères. Des faciès qui comportent des sulfures polymétalliques cuprifères et sont recouverts par des dépôts ferrugineux, sont associés à une activité hydrothermale effusive dans la caldeira de ces volcans.

Le réseau de failles transformantes et d'axes d'expansion se prolonge au nord à partir de la dorsale du Pacifique de l'Est en traversant le golfe de Californie, se poursuit le long de la faille de San Andreas sur le continent, et au nord sur le fond marin avec les crêtes de Gorda et de Juan de Fuca. La séparation entre la péninsule de Basse-Californie et le Mexique continental s'effectue sur la marge de la plaque du Pacifique et de la plaque Nord-Américaine à la vitesse de 3 à 6 cm par an. Les basaltes occupant des sites de l'embouchure du golfe de Californie sont interstratifiés avec des sédiments et des boues à smectites et sont altérés et traversés par des filons de sulfures, carbonates, argiles smectiques et minéraux zéolitiques.

Diatomaceous ooze, terrigenous silty mud and turbidite mud are up to 500 m thick and are accumulating at the rate of 100 to 250 cm/a. Extensive deposits of iron-rich talc, smectite mud, sulphide minerals and petroleum-rich sediment associated with hydrothermal effusive activity at temperatures of 280°C are found in the basin. Ledges and terraces in the North Trough are encrusted with iron and manganese oxide, smectite and talc that contains iron sulphide and minor amounts of Cu, Zn, Co, and Au. The thick section of sediment in the South Trough is intruded by a series of basalt sills and plugs. Mounds up to 100 m in diameter and 15 m high composed of smectite, detrital sediment and sulphide rest on turbidite sediments that are metamorphosed to greenschist facies at depth or near the basalt sills. Mound material around the hydrothermal vents consists of Cu, Zn and Pb sulphide, barite, talc, opaline silica, iron oxide and petroleum compounds. The petroleum, which exudes from the sediment in places, is believed to have formed by hydrothermal pyrolysis of organic matter.

Basal metalliferous sediments sampled at DSDP sites along the western margin of the continental United States and Mexico consist of reddish-brown clay and amorphous iron and manganese oxide enriched in the minor metals that are associated with dolomitic clay and basalt. Basal sediment west of the south end of the California Peninsula consists of interlayered yellow to brown iron-rich clay, sulphide-bearing sediment and black quartzose chert associated with basalt. The sulphide layers are about 35 cm thick and are composed of pyrite, chalcopyrite and sphalerite with some chert and calcite.

Basal metalliferous sediment of Late Eocene age between the Murray and Mendocino fracture zones near 140°W and at sites near 160°W in the North Pacific Ocean consists of mixed facies of yellow to brown amorphous iron and manganese oxide up to 9 m thick that contain silt-sized detrital minerals, tuff particles and montmorillonite clay, and locally manganese micronodules. Yellow-brown amorphous spherules of iron oxide 5 to 25 μm in size that are intermixed with colloidal size particles in the iron oxide beds may have formed in the same way as the granules and oolites in older iron-formations. The metalliferous facies throughout the North Pacific are considered to be protosediment of oxide facies iron-formation.

The Gorda Ridge is 160 to 330 km west of the coast of Northern California and Oregon, and extends north from Mendocino Fracture Zone to Blanco Fracture Zone. The ridge is spreading at the rate of 5 to 6 cm/a and the central rift valley narrows from 7 km in the north to about 2 km in the

Le bassin de Guaymas se compose de deux dépressions en échelon de 3 à 5 km de large et de 20 km de long, situées sur un segment en expansion rapide du réseau de failles et fossés tectoniques. Les boues à diatomées, les boues limoneuses terrigènes et les boues à turbidites atteignent parfois 500 m d'épaisseur, et s'accumulent à la vitesse de 100 à 250 cm par an. On rencontre dans le bassin de vastes dépôts de talc ferrifère, de boues à smectites, de minéraux sulfurés et de sédiments pétrolifères, associés à une activité hydrothermale effusive se déroulant à la température de 280 °C. Les corniches et terrasses de la dépression nord sont recouvertes d'une croûte d'oxydes de fer et de manganèse, de smectite et de talc contenant des sulfures de fer et des traces de Cu, Zn, Co et Au. L'épaisse tranche sédimentaire du bassin sud est traversée par une série de filons-couches et culots basaltiques. Des monticules atteignant 100 m de diamètre et 15 m de haut, et composés de smectite, de sédiments détritiques et de sulfures, reposent sur des sédiments à turbidites qui ont été métamorphisés dans le faciès des schistes verts, en profondeur ou près des filons-couches de basalte. Autour des évents hydrothermaux, les monticules sont constitués de sulfures de Cu, Zn et plomb, de barytine, de talc, si silice opaline, d'oxydes de fer, et d'hydrocarbures. On estime que le pétrole qui suinte des sédiments s'est formé par pyrolyse hydrothermale de la matière organique.

Les sédiments basaux métallifères échantillonnés dans des sites explorés dans le cadre du Programme de forage à grande profondeur au-dessous du niveau de la mer, le long de la marge ouest de la masse continentale des États-Unis et du Mexique, sont constitués d'argiles brun rougeâtre et d'oxydes amorphes de fer et de manganèse enrichis en éléments traces associés aux argiles dolomitiques et aux basaltes. Le sédiment basal à l'ouest de l'extrémité sud de la péninsule californienne est constitué d'argiles interstratifiées ferrifères, de couleur jaune à brune, de sédiments sulfurés, et d'un chert quartzeux noir associé aux basaltes. Les couches sulfurées ont environ 35 cm d'épaisseur, et sont composées de pyrite, de chalcopyrite et de sphalérite, et d'un peu de chert et de calcite.

Le sédiment métallifère basal d'âge Éocène supérieur que l'on trouve entre les zones de fractures de Murray et de Mendocino près de 140°W, et en des sites proches de 160°W dans le Pacifique du Nord, est constitué d'un faciès mixte à oxydes amorphes de fer et de manganèse, de couleur jaune à brune, atteignant parfois 9 cm d'épaisseur, et contenant des minéraux détritiques limoneux, des particules de tuf et de l'argile montmorillonitique, et localement, des micronodules de manganèse. Des sphérulites amorphes d'oxydes de fer, de couleur brun jaune, de dimensions comprises entre 5 et 25 microns, qui sont mêlées à des particules colloïdales dans les lits d'oxydes de fer, se sont peut-être formées de la même façon que les granules et oolites des formations ferrifères plus anciennes. On considère que dans tout le Pacifique du Nord, les faciès métallifères représentent le protosédiment d'une formation ferrifère à faciès oxydé.

La crête de Gorda se trouve entre 160 et 330 km à l'ouest de la côte nord de la Californie et de l'Oregon, et se prolonge vers le nord, de la zone de fractures de Mendocino à celle de Blanco. À l'emplacement de la crête, l'expansion de la croûte est de 5 à 6 cm par an, et la vallée tectonique centrale passe

Escanaba Trough in the south. Volcanic centres have been located at a number of places along the sediment-filled Escanaba Trough, and sulphide samples were dredged from along the flank of an uplifted dome in its central part. Sulphide deposits with a high content of Cu and Zn, chimneys and stacks and hydrothermal venting have been discovered in the southern trough in an area about 1 by 3 km. Metalliferous sediment composed of iron and manganese oxide and nontronite clay has been recovered from the northern part of the Escanaba Trough. Evidence of hydrothermal activity in the northern part of Gorda Ridge near Blanco Fracture Zone was found in samples of basalt that contain pyrrhotite, pyrite, sphalerite and barite.

The Juan de Fuca Ridge System, as defined in this paper, includes the related structural segments that trend north to northeast and extend northward from the Blanco Fracture Zone to the Queen Charlotte Fracture Zone. Spreading along this ridge system is taking place at the rate of 6 cm/a and evidence of hydrothermal effusion at intervals of 100 km or less along its entire length is found in the many occurrences of metalliferous sediment and active vents that have been explored. Metalliferous sediments from a deep trough at the intersection of the Blanco Fracture Zone and the Juan de Fuca Ridge have a high content of Mn and are enriched in As, Cu, Zn, and Ni.

The southern segment of the Juan de Fuca Ridge forms a narrow linear rift zone about 60 km long and 3 km wide at a water depth of 2260 m that is remarkably symmetrical in cross-section and covered by volcanic flows. Hydrothermal activity was found in 6 vent areas in the southern 20 km of the rift zone along a narrow depression in the axial valley where there has been considerable collapse of lava lakes and the pahoehoe-textured flows are highly fractured and fissured. Lavas in the axial valley are 200 years old, or even younger, and those on the ridge flanks are 15 000 to 20 000 years old and many are coated with iron and manganese oxide. Hydrothermal deposits form ledges and low mounds in the central axial zone. They are composed of angular slabs of dark grey, zinc-rich sulphide interlayered with thin oxidized crusts of iron sulphide that appear to be fragments and talus from broken vent stacks and chimneys. More porous aggregates of sphalerite, pyrite, opaline silica, hematite and barite may have been deposited in areas peripheral to the main vents. Hydrothermal plumes formed by suspended colloidal particles in vent fluids are dispersed over the southern Juan de Fuca Ridge and metals may be transported 100 km or more before they accumulate in metalliferous sediments.

The Central Segment of Juan de Fuca Ridge is offset about 3 km to the west of the Southern Segment and is about 6 km wide and 2300 to 2400 m

d'une largeur de 7 km au nord à environ 2 km dans la dépression d'Escanaba au sud. On a identifié des centres d'activité volcanique en un certain nombre d'endroits le long de la dépression d'Escanaba, qui est comblée par des sédiments, et l'on a remonté des échantillons de sulfures par dragage le long du flanc d'une dôme soulevé qui occupe la partie centrale de cette dépression. Dans une zone d'environ 1 km par 3 km, dans la dépression sud, on a découvert des gisements de sulfures caractérisés par une teneur élevée en Cu et Zn, ainsi que des cheminées, des colonnes, et des évents hydrothermaux. Dans la partie nord de la dépression d'Escanaba, on a prélevé des sédiments métallifères composés d'oxydes de fer et de manganèse et d'argile de type nontronite. On a rencontré des indices d'activité hydrothermale dans la partie nord de la crête de Gorda, près de la zone de fractures de Blanco, dans des échantillons de basaltes contenant de la pyrrhotine, de la pyrite, de la sphalérite et de la barytine.

Le système de dorsales ou crêtes de Juan de Fuca, tel que défini dans cet article, comprend les segments structuraux apparentés d'orientation nord à nord-est, qui se prolongent vers le nord de la zone de fractures de Blanco à la zone de fractures de la Reine-Charlotte. Le long de ce système de dorsales, l'expansion se produit à la vitesse de 6 cm par an, et l'on rencontre des indices d'une activité effusive hydrothermale à des intervalles de 100 km ou moins sur toutes sa longueur; ces indices sont les nombreuses venues de sédiments métallifères et les nombreux évents actifs que l'on a explorés. Des sédiments métallifères provenant d'une fossé profonde située à l'intersection de la zone de fractures de Blanco et de la crête de Juan de Fuca ont une teneur élevée en Mn et sont enrichis en As, Cu, Zn et Ni.

Le segment sud de la crête de Juan de Fuca forme d'étroites zones linéaires d'effondrement tectonique, d'environ 60 km de long et 3 km de large, à 2260 m de profondeur au-dessous de la surface de la mer, remarquablement symétriques en coupe transversale et recouvertes par des coulées volcaniques. On a observé une activité hydrothermale dans six zones d'évents, sur une longueur de 20 km, dans la partie sud du fossé tectonique, le long d'une étroite dépression de la vallée axiale où a eu lieu un effondrement considérable des lacs de lave, et où les coulées de type pahoéhoé sont fortement fracturées et fissurées. Les laves de la vallée axiale ont 200 ans ou même moins, celles des flancs de la crête 15 000 à 20 000 ans, et un grand nombre d'entre elles sont recouvertes d'un enduit d'oxydes de fer et de manganèse. Les dépôts hydrothermaux forment des corniches et des monticules de faible élévation dans la zone axiale centrale. Ils sont composés de dalles anguleuses de sulfures riches en zinc, de couleur gris sombre, interstratifiées avec de fines croûtes oxydées de sulfures de fer qui semblent être des fragments et éboulis provenant de cheminées et colonnes d'évents effondrés. Il est possible que des agrégats plus poreux de sphalérite, de pyrite, de silice opaline, d'hématite et de barytine, se soient déposés tout autour des principaux évents. Les panaches hydrothermaux que créent les particules colloïdales en suspension dans les fluides s'échappant des évents, se dispersent sur la partie sud de la crête de Juan de Fuca, et les métaux sont parfois transportés à 100 km ou plus, avant de se déposer et de s'accumuler dans les sédiments métallifères.

deep. A prominent central ridge extends north to a split volcano where there are low temperature hydrothermal deposits and the axial rift zone swings westward to Axial Seamount. This submarine volcano at the intersection of the axial valley and the Cobb-Eickelberg Seamount chain has a large caldera about 6 km long and 4 km wide at a depth of 1540 m, that is fissured and faulted at the intersection of the spreading axis and the north caldera wall. Black and white plumes exhale from chimneys up to 10 m high in a large hydrothermal field at the base of the southwest caldera wall and water temperatures range from 30 to 293° C. Red-brown sediment along the ridge axis on the north side of the caldera consists of nontronite clay and amorphous iron oxide and silica. Hydrothermal venting and a profusion of worms and fauna occur along a fissure that extends south from the north wall of the caldera floor with fluids venting at 35° C. Chimneys up to 12 m high east of this fissure are composed of spongy textured sulphide and sulphate minerals, and samples consist of barite, amorphous silica, sphalerite, marcasite, pyrite, anhydrite, galena, copper-iron sulphides, and tetrahedrite. Analyses of the samples indicate up to 28 % Zn, 5 % Fe, 0.3 % Cu, 0.6 % Pb, 15 % Ba, 41 % Si, 342 ppm Ag, 740 ppm Cd, 45 ppm Mo, 32 ppm Ni, 1300 ppm Mn and 5 to 6 ppm Au.

The Northern Segment of the Juan de Fuca Ridge system extends north from Axial Seamount area to the Cobb Offset fracture zone, and the Endeavour Ridge segment continues north from Cobb Offset to the Sovanco Fracture Zone. The Cobb Offset is a broad transform fault zone that trends northeast along which the Northern Juan de Fuca Ridge segment and the Endeavour Ridge segment are offset about 32 km with lefthand lateral displacement. The topography of ridge segments north and south of the offset zone changes from V-shaped valleys and hills of low relief to graben-like depressions in the offset zone where the sediments are tilted and disturbed. Anomalous geothermal gradients and evidence of hydrothermal venting are found in an area about 100 km north of Axial Seamount, where the rift valley is 1 km wide and covered by sheet flows, and in the large area of the Cobb Offset zone near the ridge axis. Iron-rich nontronite clay and manganese oxide sediment were dredged from the north side of the Cobb Offset zone. Samples of green nontronite clay and amorphous iron oxide contain up to 52% SiO_2, 25% Fe, 11% Mn, 6% Al, 5% Na and K, and a high content of Ba, Zn, Cu, Ni, Rb, Sr, and REE.

The Endeavour Ridge segment extends north from the Cobb Offset to the Sovanco Fracture zone and is divided into two sections about 13 km apart at Endeavour Seamount. Active spreading on the southern part of the Endeavour Ridge transfers to

Le segment central de la crête de Juan de Fuca est décalé d'environ 3 km à l'ouest du segment sud, et a environ 6 km de large et 2300 à 2400 m de profondeur au-dessous de la surface de la mer. Une grande crête centrale se prolonge au nord jusqu'à un volcan divisé en deux parties, où se trouvent des gîtes hydrothermaux de basse température, et où la zone axiale du fossé d'effondrement vire vers l'ouest en direction du guyot axial. Ce volcan sous-marin se trouve à l'intersection de la vallée axiale, et la chaîne de guyots de Cobb-Eickelberg comporte une vaste caldeira d'environ 6 km de long et 4 km de large, à la profondeur de 1540m; cette caldeira est fissurée et faillée à l'intersection de l'axe d'expansion et de la paroi nord de la caldeira. Des panaches noirs et blancs s'échappent de cheminées atteignant parfois 10 m de haut dans un vaste champ hydrothermal à la base de la paroi sud-ouest de la caldeira, et la température de l'eau se situe entre 30° et 293°C. Des sédiments brun rouge, qui suivent l'axe de la crête du côté nord de la caldeira, sont constitués de nontronite et d'oxydes de fer amorphes, et de silice. On rencontre une activité hydrothermale effusive et une grande abondance d'annélides et autres éléments de la faune, le long d'une fissure qui se prolonge vers le sud à partir de la paroi nord du plancher de la caldeira; des fluides s'échappent de cette fissure à la température de 35°C. Des cheminées atteignant 12 m de haut à l'est de cette fissure sont composées de minéraux sulfurés et sulfatés de texture spongieuse, et l'on a recueilli des échantillons composés de barytine, de silice amorphe, de sphalérite, de marcassite, de pyrite, d'anhydrite, de galène, de sulfures de cuivre et de fer, et de tétrahédrite. Les analyses des échantillons indiquent que ceux-ci contiennent jusqu'à 28 % de Zn, 5 % de Fe, 0,3 % de Cu, 0,6 % de Pb, 15 % de Ba, 41 % de Si, 342 ppm d'Ag, 740 ppm de Cd, 45 ppm de Mo, 32 ppm de Ni, 1300 ppm de Mn et 5 à 6 ppm d'Au.

Le segment nord du système de dorsales de Juan de Fuca se prolonge vers le nord à partir du guyot axial jusqu'à la zone de failles transformantes de Cobb, et le segment de la crête d'Endeavour se continue vers le nord, de la faille transformante de Cobb à la zone de fractures de Sovanco. La zone transformante de Cobb est une vaste zone de failles transformantes d'orientation nord-est, le long de laquelle le segment nord de la crête de Juan de Fuca et le segment de la crête d'Endeavour sont décalés d'environ 32 km et montrent un déplacement latéral sénestre. La topographie des segments de la crête, au nord et au sud de la zone transformante, passe de vallées en V et de collines de faible élévation à des dépressions de type graben dans la zone transformante, où les sédiments sont inclinés et perturbés. On a mesuré des gradients géothermiques anormaux, et observé des indices d'activité hydrothermale effusive dans une zone située à environ 100 km au nord du guyot axial, où la vallée tectonique a 1 km de large et où elle est recouverte par des coulées en nappes, ainsi que dans la vaste région de la zone transformante de Cobb, près des axes des crêtes. On a ramené par dragage des nontronites ferrifères et des sédiments contenant des oxydes de manganèse, sur le côté nord de la zone transformante de Cobb. Des échantillons de nontronite verte et d'oxydes de fer amorphes contiennent jusqu'à 52 % de Si, 25 % de Fe, 11 % de Mn, 6 % d'Al, 5 % de Na et K, et montrent une teneur élevée en Ba, Zn, Cu, Ni, Rb, Sr et en terres rares.

the West Valley section, and the trend of the southern section can be traced north along strike through a deep sediment-filled trough known as Middle Valley.

Vent sites in the southern section of Endeavour Ridge at 47°56'N are located along the western wall of a graben within a perched basin about 40 to 50 m above the floor of the axial depression. Hydrothermal venting at temperatures from 350 to 400° C from sulphide chimneys and fissures, a large number of tube worm colonies, numerous sulphide deposits, low temperature vents and extensive deposits of nontronite clay mark this large hydrothermal field. There are numerous other vent sites along the Ridge axis. Large samples dredged from the site consist predominantly of iron sulphide and amorphous silica and complex mineral assemblages of pyrite, marcasite, wurtzite, chalcopyrite, cubanite, pyrrhotite, galena and sphalerite, that are associated with barite, amorphous silica, chalcedony and anhydrite. Growth rates of the sulphide chimneys are about 1.2 cm/a and temperatures of the high alkaline fluids that contain radon range from 50 to 400° C. Sulphide structures rich in Cu and Zn on the west margin of the axial valley at 47°57'N are associated with sediment and lava. Hydrothermal fluids with a high chloride content are being discharged over hundreds of metres along the base of these coalesced sulphide structures. Active spreading is offset to the western section of Endeavour Ridge and continues north to Sovanco Fracture Zone.

Middle Valley, extending along strike from the southern section of Endeavour Ridge across the Cobb Offset zone, marks part of a "failed rift" system and is filled by a thick sequence of turbidite. A chain of seven mounds a few hundred metres in diameter and rising 60 m above the valley floor extends along the east side of the valley where the water depth is about 2400 m and there is anomalously high heat flow. The mounds have simple to complex morphology, show diffuse seismic profiles, are associated with hydrothermal and noncalcareous indurated sediments, and have formed above a sequence of lutite and clastic sediments that is about 200 m thick. The mounds are composed of sulphide and lutite muds with complex sedimentary and breccia features. A core 2.4 m long from one of the mounds consists of alternating beds of coarse clastic sulphide, black sulphide mud, brown lutite mud and sulphide. The various bands have been described as brown hydrothermal mud with rusty clasts of oxidized sulphide up to 5 mm, black sulphide mud with streaks of barite and talc, angular 3 cm clasts of sulphide in a matrix of granular sulphide, black gelatinous sulphide mud, angular to subrounded 8 cm clasts of sulphide in grey hemipelagic mud and black granular sulphide mud.

Le segment de la crête d'Endeavour se prolonge vers le nord à partir de la zone transformante de Cobb jusqu'à la zone de fractures de Sovanco, et se subdivise en deux sections distantes d'environ 13 km à l'emplacement du guyot Endeavour. Le processus actif d'expansion qui se déroule dans la partie sud de la crête d'Endeavour est transmis à la section de la vallée ouest, et l'on peut suivre l'orientation de la section sud vers le nord, le long d'une fosse profonde comblée par des sédiments, appelée vallée intermédiaire.

Les sites d'évents, dans le segment sud de la crête d'Endeavour, à 47°56'N, suivent la paroi ouest d'un graben, à l'intérieur d'un bassin perché situé à environ 40 à 50 m au-dessus du plancher de la dépression axiale. La présence d'une activité hydrothermale effusive à des températures comprises entre 350° et 400°C, provenant de cheminées et fissures dans des roches sulfurées, et l'existence d'un grand nombre de colonies de vers polychètes, de nombreux gisements de sulfures, d'évents de basse température, et d'importants dépôts de nontronite, marquent ce vaste champ hydrothermal, et il existe de nombreux autres sites d'évents le long de l'axe de la crête. Les gros échantillons prélevés par dragage sur ce site sont principalement constitués de sulfures de fer, de silice amorphe et d'assemblages minéraux complexes de pyrite, de marcassite, de wurtzite, de chalcopyrite, de cubanite, de pyrrhotine, de galène et de sphalérite, qui sont associés à de la barytine, de la silice amorphe, de la calcédoine et de l'anhydrite. Les cheminées de matériaux sulfurés se développent à la vitesse d'environ 1,2 cm/an, et la température du fluide fortement alcalin contenant du radon, se situe entre 50 et 400°C. Les structures composées de sulfures riches en Cu et Zn, situées sur la marge ouest de la vallée axiale à 47°57'N, sont associées à des sédiments et à des laves. Des fluides hydrothermaux caractérisés par une forte teneur en chlorures se déversent sur des centaines de mètres, en suivant la base de ces structures composées de produits sulfurés et réunies par coalescence. Les processus actifs d'expansion de la croûte terrestre sont décalés vers la section ouest de la crête d'Endeavour, et se prolongent vers le nord jusqu'à la zone de fractures de Sovanco.

La vallée intermédiaire, qui s'étend de la section sud de la crête d'Endeavour à travers la zone transformante de Cobb, correspond à une partie d'un système de "fossé tectonique avorté", et est comblée par une épaisse succession de turbidites. Une chaîne de sept monticules, qui ont quelques centaines de mètres de diamètre et dominent de 60 m le fond de la vallée, longe la paroi est de la vallée, à environ 2400 m de profondeur au-dessous de la surface de la mer, et l'on y a noté un flux thermique anormalement élevé. Les monticules ont une morphologie simple à complexe, donnent des profils sismiques diffus, sont associés à des sédiments indurés d'origine hydrothermale, non calcaires, et se sont formés au-dessus d'une succession de lutites et de sédiments clastiques d'environ 200 m d'épaisseur. Les monticules sont composés de boues sulfurées et de boues de type lutite, et sont caractérisés par des structures sédimentaires et bréchiques complexes. Une carotte de 2,4 m de long, prélevée dans l'un des monticules, est composée de lits alternés de sulfures clastiques grossiers, de boues sulfurées noires, de lutites brunes et de sulfures. On a décrit les diverses structures rubanées comme étant composées de boues hydrothermales brunes accompagnées de clastes de couleur rouille

Sulphide fragments consist of aggregates of pyrite, pyrrhotite, sphalerite, chalcopyrite, isocubanite, marcasite, and galena in a matrix or cemented by barite, amorphous silica and talc. The sulphide aggregates contain up to 4.6 % Zn, 0.4 % Cu, 7.5 ppm Ag, 165 ppm Mo, 119 to 158 ppb Au, 3 % Ba and 7 % MgO, 248 ppm As, 46 ppm Sb and 136 ppm Se.

A core of sediment from 2.4 m beneath the surface of a mound consists of thin soft brown bands high in Ba, Mn, and organic carbon that are interbedded with calcareous grey lutite and noncalcareous indurated layers containing soft angular clasts. The various beds in this core comprise olive-grey indurated sediment containing clasts of sediment, worm burrows, sponge spicules, and manganese oxide; angular semi-indurated sediment fragments in a matrix of calcareous soft lutite mud; lithified lutite; laminated indurated silt;, dark brown unlithified bands interbedded with olive-grey lutite; siliceous biogenic debris and radiolarian tests, silty clay, and red ferruginous particles. This sediment contains up to 67 % SiO_2, 17 % Al_2O_3, 7.8 % CaO, 5 % Na_2O, 3 % K_2O, 5 % Fe, 0.5 % Mn and a high content of trace elements typical of many hydrothermal smectite sediments.

Explorer Ridge extends northeast from its intersection with Sovanco Fracture Zone at 49°20'N and 130°15'W to a northwest trending fracture zone at 49°55'N and 130°15'W. The ridge is divided into two sections north of this fracture zone and the western section is offset to the west at the southeast edge of Dellwood Seamounts before it continues north to Paul Revere Ridge. The ridge is marked by intensely faulted horst and graben topography and covered with red to yellow metalliferous sediment. The central axial valley in the southern segment of the ridge is about 1.7 km wide and extends northeast for 30 km where it divides into two narrow parallel valleys referred to as the East and West valleys. Water depths decrease from 2000 m in the south to 1760 m in the area of low relief near the northern transverse valley. The western and eastern sections of the ridge north of this transverse valley are covered by sediment and older lava flows. The main hydrothermal field on the ridge is located in the southern segment of the ridge in East Valley in the Magic Mountain area at 49°45'N and 130°15'W.

About 60 sulphide deposits associated with active vent sites are located along an 8 km section of the east wall of East Valley. Metalliferous sediment and altered basalt are associated with a second large vent field at the north end of the West Valley. Seven large sulphide deposits at Magic Mountain occur near transverse faults and consist of mounds up to 200 m long and 100 m wide and 5 to 10 m thick that are made up of smaller

composés de sulfures oxydés et atteignant au maximum 5 mm, de boues sulfurées noires avec de fines bandes de barytine et de talc, de clastes anguleux de 3 cm, composés de sulfures dans une matrice de sulfures granulaires, de boues sulfurées gélatineuses et noires, de clastes angulaires à subarrondis de sulfures atteignant 8 cm, contenus dans des boues hémipélagiques grises et des boues sulfurées avec matériaux granulaires noirs. Les fragments de minéraux sulfurés sont constitués d'agrégats de pyrite, de pyrrhotine, de sphalérite, de chalcopyrite, d'isocubanite, de marcassite et de galène, inclus dans une matrice ou cimentés par de la barytine, de la silice amorphe et du talc. Les agrégats sulfurés contiennent jusqu'à 4,6 % de Zn, 0,4 % de Cu, 7,5 ppm d'Ag, 165 ppm de Mo, 119 à 158 ppb d'Au, 3 % de Ba et MgO, 248 ppm d'As, 46 ppm de Sb et 136 ppm de Se.

Une carotte de sédiment prélevée à 2,4 m au-dessous de la surface d'un monticule, était constituée de minces bandes de matériaux bruns et tendres riches en Ba, Mn et en carbone organique, interstratifiées avec une lutite calcaire grise et des couches indurées non calcaires contenant des clastes anguleux. On a décrit la lithologie des divers lits qui apparaissent dans cette carotte, de la façon suivante : sédiment induré de couleur gris-olive, contenant des clastes sédimentaires, des galeries creusées par des vers, des spicules d'éponges et des oxydes de manganèse; fragments sédimentaires anguleux semi-indurés dans une matrice de boue calcaire et tendre de type lutite; lutite lithifiée; limon induré, laminé; bandes brun sombre non lithifiées, interstratifiées avec une lutite gris olive; débris siliceux d'origine biologique avec tests de radiolaires, argiles limoneuses et particules ferrugineuses rouges. Ce sédiment contient jusqu'à 67 % de SiO_2, 17 % d'Al_2O_3, 7,8 % de CaO, 5 % de Na_2O_2, 3 % de K_2O, 5 % de Fe, 0,5 % Mn et une forte concentration d'éléments-traces typiques de nombreux sédiments hydrothermaux du type smectite.

La dorsale d'Explorer s'étend vers le nord-est, depuis son intersection avec la zone de fractures de Sovanco à 49°20'N et 130°15'W à une zone de fractures d'orientation nord-ouest à 49°55'N et 130°15'W. La dorsale est divisée en deux sections au nord de cette zone de fractures, et la section ouest est décalée à l'ouest, sur le bord sud-est des guyots Dellwood, puis se continue vers le nord jusqu'à la crête Paul Revere. L'emplacement de la dorsale est marqué par une topographie fortement faillée à horsts et grabens, et cette dorsale est couverte de sédiments métallifères rouges à jaunes. La vallée axiale centrale du segment sud de la dorsale a environ 1,7 km de large et se prolonge vers le nord-est sur 30 km, puis se subdivise en deux étroites vallées parallèles appelées vallée Est et vallée Ouest. La profondeur passe de 2000 au-dessous du niveau de la mer au sud à 1760 m dans la zone de relief peu prononcé, près de la vallée transversale nord. Les sections ouest et est de la dorsale au nord de cette vallée transversale sont recouvertes de sédiments et de coulées de laves plus anciennes que ceux-ci. Le principal champ hydrothermal de la dorsale se situe dans le segment sud de celle-ci, dans la vallée Est, à l'intérieur de la zone de Magic Mountain à 49°45'N et 130°15'W.

On a répéré environ 60 gîtes sulfurés associés à des sites d'évents actifs, le long d'une section de 8 km de la paroi est de la vallée Est. Des sédiments métallifères et des basaltes sont

coalesced mounds. The mounds appear to develop by the accumulation of sulphide talus from the erosion and collapse of chimney structures, and by hydrothermal precipitation from beneath and are mantled by metalliferous sediment and oxidized material. Some mounds are zoned from Cu-Fe-rich massive sulphide at the base to Zn-rich sulphide to silica and barium rich cappings. The Parizeau deposit is cut by a fault and the stratigraphy from its base upward consists of stockwork mineralization in pillow lava, 10 m of massive sulphide that is Cu-rich at the base and Zn-rich at the top, chimneys and spires of barite, and red oxidized metalliferous sediment 1 to 4 cm thick. The mounds consist of about 20 % barite, 20 % silica, 20 % sphalerite and wurtzite, 17 % chalcopyrite, 20 % pyrite and marcasite, and the sulphide talus is coated with amorphous iron and manganese oxide. The average content of 8 sulphide samples is 9 % Zn, 8 % Cu, 11 % Fe, 0.1 % Pb, 19.2 % SiO_2, 8 % Ba, 112 ppm Ag, and 0.6 ppm Au.

Hydrothermal plumes from the northern part of Explorer Ridge have been traced westward from Magic Mountain for more than 8 km in a zone 20 to 340 m above the seafloor. Plume water contained up to 160 g/l of colloidal size orange-brown amorphous Fe-Si-P-S phases and Mg-silicates including about 274 nmole/kg of Fe and 63 nmole/kg of Mn.

Metalliferous sediments in the northeast and northwest segments of Explorer Ridge are composed of iron and manganese oxides and yellow-green nontronite clay and have a high content of minor elements. The siliceous Fe-rich oxide facies on Dellwood Seamount, on the Dellwood Knolls and in the northern segments of Explorer Ridge have been deposited in the initial stages of hydrothermal effusion associated with the development of spreading and northern migration of the Juan de Fuca Ridge System.

Conclusions

It is difficult to define sedimentary environments, distribution of sedimentary facies, the extent of mineral deposition and hydrothermal effusive processes and the geological context of seabed mineral deposits because of the lack of information and limitations in sampling methods. Dredge samples are usually accompanied by very little information about their setting, samples obtained using manned submersibles provide two-dimensional and some third-dimensional information, and individual cores provide vertical stratigraphic but little areal information. Many of the seabed mineral deposits are only known through one sampling method or by one small sample and interpretations of geological settings may be tenuous. Information is limited

associés à un second vaste champ d'évents à l'extrémité nord de la vallée Ouest. On a découvert sept vastes gîtes sulfurés à Magic Mountain près de failles transversales; ceux-ci sont constitués de monticules formés par fusionnement d'autres monticules plus petits, et atteignent parfois 200 m de long, 100 m de large et 5 à 10 m d'épaisseur. Il semble que ces monticules se soient formés par accumulation d'éboulis sulfurés résultant de l'érosion et de l'effondrement des structures en cheminées, et par précipitation hydrothermale au-dessous des débris; ils sont recouverts d'un manteau de sédiments métallifères et de matériaux oxydés. Certains monticules montrent une zonation allant de sulfures massifs riches en Cu et Fe à leur base, à des sulfures riches en Zn, puis à des terrains de couverture riches en baryum et silice. Le gisement de Parizeau est recoupé par une faille; dans la colonne stratigraphique, de la base vers le haut, on observe une minéralisation de type stockwerk dans une lave en coussins, puis une couche de 10 m de sulfures massifs riches en Cu à sa base et en Zn à son sommet, des cheminées et colonnes de barytine, et un sédiment métallifère oxydé de couleur rouge, de 1 à 4 cm d'épaisseur. Les monticules sont composés d'environ 20 % de barytine, 20 % de silice, 20 % de sphalérite et de wurtzite, 17 % de chalcopyrite, 20 % de pyrite et de marcassite, et les éboulis sulfurés sont recouverts d'un placage d'oxydes de fer et de manganèse amorphes. En moyenne, les huit échantillons de sulfures contiennent 9 % de Zn, 8 % de Cu, 11 % de Fe, 0,1 % de Pb, 19,2 % de SiO_2, 8 % de Ba, 112 ppm d'Ag, et 0,6 ppm d'Au.

On a répéré les panaches hydrothermaux issus de la partie nord de la dorsale d'Explorer, en direction de l'ouest à partir de Magic Mountain, sur plus de 8 km, dans une zone de 20 à 340 m au-dessus du fond marin. L'eau des panaches contenait jusqu'à 1600 g/L des phases Fe-Si-P-S, sous forme de produits amorphes et colloïdaux de couleur brun orange, et des silicates de Mg, y compris environ 274 nmole/kg de Fe et 63 nmole/kg de Mn.

Les sédiments métallifères des segments nord-est et nord-ouest de la dorsale d'Explorer sont composés d'oxydes de fer et de manganèse ainsi que de nontronite de couleur verte à jaune, et montrent une concentration élevée en éléments traces. Les faciès oxydés ferrifères et siliceux que l'on trouve sur le guyot Dellwood, sur les buttes Dellwood et dans les segments nord de la dorsale d'Explorer se sont déposés pendant les stades initiaux de l'activité effusive hydrothermale associée à l'expansion croissante et à la migration vers le nord du système de dorsales de Juan de Fuca.

Conclusion

Il est difficile de définir les milieux sédimentaires, la distribution des faciès sédimentaires, l'étendue et l'importance des dépôts de minéraux et des processus effusifs de type hydrothermal, ainsi que le contexte géologique des gîtes minéraux du fond marin, en raison du peu d'information dont on dispose à ce sujet et des limitations des méthodes d'échantillonnage. Généralement, lorsqu'on prélève des échantillons par dragage, on obtient très peu de données sur leur environnement; les échantillons que l'on prélève en employant des submersibles pilotés nous donnent de l'information en deux dimensions et parfois en trois dimensions; et les carottes indi-

but a good indication of the main types, characteristics and genesis of recently formed mineral occurrences can be gained through collective study of the available sample data. The following general conclusions emerge from this broadly based study of seabed mineral occurrences and from study of analogous or similar types of mineral deposits on land.

1. Deposition of metalliferous sediment by hydrothermal effusive processes commonly takes place where deep fracture zones coincide with anomalously high thermal gradients in the oceanic lithosphere.

2. Metalliferous sediment facies actively forming on the seabed are similar in their composition and geological setting to ancient mineral deposits and are recognized as the primary or prototype sediment of iron-formation, stratafer chemical sediments and related mineral deposits. The seabed metalliferous deposits can provide direct guidelines for exploration, for defining the nature and characteristics of hydrolithic sedimentary deposits, and for understanding the genesis of the large sedimentary mineral deposits that provide the major part of world mineral resources.

3. Polymetallic sulphide deposits occur in stockworks and as bedded sediments, mounds, crusts and stacks close to high temperature hydrothermal vents, and bedded or thinnly layered iron sulphide facies may extend to areas distal from the effusive centres.

4. Zoning exists in most of the sediment, crusts, mounds and chimneys formed around high temperature vents, and transitional zoning outward from the vent from iron and copper to zinc sulphides, to iron and manganese sulphide and oxide facies follows high to low temperature gradients.

5. Common sequences in the distribution of facies in the metalliferous sediments show sulphide facies deposition close to high temperature effusive centres, iron oxide and silicate facies are intermediate, and manganese and iron bearing facies are deposited from cooler hydrothermal vents and in areas distal from centres of hydrothermal discharge. Transitions and overlapping of facies types are normally expected. Deposition of facies in zones above the depth of carbonate compensation may deviate from this sequence and iron and manganese carbonate facies may extent from vent to distal areas.

6. Sequential development of different facies of metalliferous sediment during the evolution of spreading ridge systems shows deposition of siliceous iron and manganese oxide facies in the initial and cooler stages of effusive hydrothermal activity along ridge axes, and continued deposition of these facies in the direction of propagation of a ridge system. Facies development extends laterally from polymetallic sulphide and iron sulphide

viduelles nous fournissent des données stratigraphiques verticales, mais très peu d'information quant à la superficie. Un grand nombre des gîtes minéraux que l'on a découverts n'ont été explorés que par une seule méthode d'échantillonnage, ou ne sont connus que par l'étude d'un échantillon de petite taille, et il est parfois difficile d'interpréter leur cadre géologique. Même si l'information est limitée, on peut obtenir des indices précis sur les principaux types, caractéristiques et modes de genèse des venues minéralisées récemment formées, en regroupant et en examinant toutes les données fournies par les échantillonnages. A partir de cette étude très générale des venues minéralisées du fond marin, et de l'examen des types analogues ou similaires de gîtes minéraux terrestres, on en est arrivé aux conclusions générales suivantes:

1. Généralement, durant les processus hydrothermaux de type effusif, le dépôt de sédiments métallifères a eu lieu là où des zones de fractures profondes coïncident avec des gradients thermiques anormalement élevés de la lithosphère océanique.

2. Les faciès sédimentaires métallifères qui apparaissent actuellement sur le fond marin sont similaires, du point de vue de leur composition et de leur cadre géologique, à ceux des anciens gîtes minéraux, et ont été identifiés comme les sédiments primaires ou "prototypes" des formations ferrifères, des sédiments chimiques ferrifères de type statiforme et des gîtes minéraux apparentés. Les gîtes métallifères du fond marin peuvent directement servir d'indicateurs à l'exploration, si l'on définit leur nature et leurs caractéristiques, et leur étude nous permet de mieux comprendre la genèse des vastes gîtes minéraux sédimentaires qui constituent la majeure partie des ressources minérales du globe.

3. On rencontre des gîtes sulfurés polymétalliques dans les stockwerks et dans des sédiments stratifiés, monticules, croûtes et cheminées proches d'évents hydrothermaux de haute température; des faciès lités ou finement stratifiés à sulfures de fer peuvent apparaître même dans des zones très distantes des centres d'activité hydrothermale effusive.

4. On observe une zonation dans la plupart des sédiments, croûtes, monticules et cheminées formés autour d'évents de haute température, ainsi qu'un type de zonation transitionnelle autour de l'évent; les sulfures de fer et de cuivre font place aux sulfures de zinc, puis aux sulfures de fer et de manganèse et enfin aux faciès oxydés, à mesure qu'on passe de gradients thermiques élevés à faibles.

5. Les séquences habituelles de distribution des faciès sédimentaires de type métallifère indiquent le dépôt de faciès sulfurés à proximité des centres effusifs de haute température, de faciès à oxydes de fer et à silicates dans la zone de température intermédiaire, et enfin de faciès manganésifères et ferrifères par précipitation à partir d'évents hydrothermaux moins chauds, ou à grande distance des centres d'activité hydrothermale effusive. On observe souvent des transitions et recouvrements des types de faciès. Les faciès qui sont apparus dans des zones au-dessus de la profondeur de compensation des carbonates peuvent dévier de cette séquence, des faciès carbonatés à fer et manganèse peuvent exister, des évents jusqu'à de grandes distances de ceux-ci.

facies proximal to vent areas, to silicate facies and carbonate facies in relatively shallow water, and to iron oxide and manganese facies distal from hydrothermal centres.

7. Hydrothermal effusive systems are frequently initiated at the intersection of ridge axes and transverse faults, and achieve their greatest intensity and maturity in these areas.

8. Deposition of the higher temperature polymetallic sulphide mineral assemblages usually takes place in the tectonically active and faster spreading segments of the propagating parts of ridges. As ridge systems develop the earlier formed metalliferous deposits are moved laterally from the axial zone and become covered with clastic sediment, tuff and lava.

9. Metalliferous sediment and manganese nodules may accumulate in basins off the ridge axes throughout the entire period of ridge development if clastic sedimentation is low.

6. Le développement séquentiel de divers faciès sédimentaires de type métallifère, durant l'évolution des systèmes de dorsales en rapport avec l'expansion de la croûte terrestre, se traduit par le dépôt de faciès siliceux à oxydes de fer et de manganèse, durant les étapes initiales et plus froides d'activité hydrothermale effusive le long des axes des crêtes ou dorsales, et par le dépôt continu de ces faciès dans la direction de propagation du système de dorsales. Latéralement, les faciès évoluent de faciès à sulfures polymétalliques et sulfures de fer à proximité des évents, à des faciès silicatés et faciès carbonatés en eau relativement peu profonde, et à des faciès à oxydes de fer et de manganèse à relativement grande distance des centres d'activité hydrothermale.

7. Fréquemment, les systèmes effusifs de type hydrothermal apparaissent à l'intersection des axes de dorsales et des failles transversales, et atteignent leur intensité et maturité maximales dans ces zones.

8. Généralement, le dépôt d'assemblages minéraux sulfurés et polymétalliques de haute température a lieu dans les segments tectoniquement actifs et en expansion rapide des portions de dorsales en cours de propagation. A mesure que se développe un système de dorsales, les gîtes métallifères déjà formés sont latéralement déplacés par rapport à la zone axiale et progressivement recouverts de sédiments clastiques, de tufs et de laves.

9. Les sédiments métallifères et nodules de manganèse peuvent s'accumuler dans des bassins au large des axes des dorsales, durant toute la période d'évolution de celles-ci, lorsque le sédimentation clastique est faible ou minimale.

INTRODUCTION

Technology developed in recent years has enabled direct observation and research on the deep parts of the seafloor. Exploration of the seafloor using manned submersibles and remotely operated vehicles has been highly rewarding scientifically and reconnaissance surveys have had a profound impact on the earth sciences and on the international affairs of many countries. Mineral deposits occur on the seafloor in many parts of the world and numerous separate research groups have studied them.

Map 1659A, a world map with descriptive notes, shows the different kinds of metallic mineral occurrences on the deep seabed, their location with respect to major geological features, and their proximity to land areas. Geological features are highly generalized on the map. Most of the mineral occurrences and hydrothermal fields described occur in water depths below 500 m. Deposits of metalliferous sediment in shallow water that are similar to those on the deep seabed are also described.

Map legend and symbols

Five main features are shown.

1) continents and landmass areas;
2) seabed areas up to 370 km from land;
3) major tectonic features including zones of subduction, collision, axial lines of spreading ridges, and major transform-faults;
4) occurrences of manganese nodules and crusts with demarcation of areas where nodules are known to have a higher content of nickel and copper, and in some cases cobalt;
5) various types of metalliferous sediment and crusts composed of chemically precipitated polymetallic sulphide, iron and manganese-rich facies that formed on or near the surface of the seabed, and the chimneys, stacks and mounds associated with them in the vicinity of hydrothermal vents; and veins, stockworks, and disseminated minerals that occur in bedrock below the seafloor.

The map symbols are composed of several parts that depict the location, form and composition of the mineral occurrences;

i) triangles for deposits that formed around hydrothermal vents or in veins and stockworks in the bedrock below the vents;
ii) squares for basal metalliferous sediments; and
iii) circles for metalliferous sediments and crusts and stratiform accumulations in pods and mounds.

The composition of the deposits is shown by;

i) diagonal lines on the symbols for deposits containing sulphide minerals;
ii) horizontal lines for iron-rich deposits; and
iii) vertical lines for manganese-rich deposits.

Tectonic features

Principal tectonic features shown on Map 1659A include spreading ridges, transform faults, and zones of subduction, thrusting and collision. Global tectonic data were compiled from sources listed in the bibliography.

Spreading ridges are developed where parts of the earth's crust or plates are separating along linear belts at rates of 1 to 17 or more cm/a. The direction of movement of the plates at the ridges is indicated on the map by arrows with the rate of movement, measured in centimetres per year, shown beside the arrows. The spreading ridges form global systems along which major volcanism, hydrothermal circulation and deep-seated fractures develop. The ridge axes are marked by linear fault zones, narrow troughs, and horsts and grabens flanked by linear fault scarps, and are covered in places by volcanic flows and tuffs and various kinds of clastic and pelagic sediments. Hotsprings and extensive effusive hydrothermal activity takes place along active spreading segments of the ridges. Immense amounts of mineralized fluid and thermal energy are discharged from the seabed through open vents and fissures, from seepage springs and by exhalation through the bedrock.

The transform fault zones are deep-seated fracture systems that separate segments of the spreading ridges and form an integral part of the major tectonic ridge system. They are important focal areas for seismic activity, volcanism and effusive hydrothermal activity.

The subduction zones form linear structural segments thousands of kilometres long and are focal areas for intense volcanic and hydrothermal effusive activity. Subduction zones are formed where one plate or a part of the earth's crust is underthrust or overridden by another plate. These zones are usually marked by thrust faulting, folding, uplift, and seismic and volcanic activity. Block faulting is common in the back-arc basins that develop along the edges of a linear subduction belt. The volcanic arcs, back-arc basins and other tectonic features that are prominent in subduction zones are not distinguished on Map 1659A.

Seamounts are formed in conjunction with the spreading ridges, subduction zones, and hot spots in the oceanic crust and are too numerous to plot on the map. They form circular, conical or irregular structures that may rise more than 1000 m above the seafloor. They are developed by a combination of geological processes involving, volcanism, tectonic uplift, folding, and buckling of the earth's crust.

Volcanism

Volcanic activity is an integral part of the development of a tectonic ridge system. It is extensively developed where ridge systems intersect thinner parts of the oceanic crust and is prominently associated with deep seated fracture systems. Lava flows, tuff and pyroclastic rocks intermediate to mafic and occasionally ultramafic in composition are typically part of these tectonic belts.

Mineral occurrences

Two major metallogenetic types of mineral occurrences are commonly found on the seafloor: manganese nodules and crusts, and metalliferous sediments, crusts and mounds.

The manganese nodules and crusts, which are distributed widely in major deep ocean basins, are formed through sedimentary, concretionary and biogenic processes. The metals contained in them which include iron, manganese, nickel, copper, and cobalt, are derived from hydrothermal, diagenetic, halmyrolytic, and sedimentary sources. Map 1659A shows nodule distribution mainly at depths greater than 2000 m by light and dark stippled areas. Nodules from the darker stippled areas have a combined content of copper, nickel and cobalt greater than one per cent and may be important sources of these metals in the future. Regions with nodules containing higher concentrations of cobalt have not been delineated.

The metalliferous sediments, crusts and mounds located along fractures, faults and the spreading ridges on the seafloor are formed by precipitation of iron, manganese, copper, zinc, lead, cobalt, silver, gold and other metals from solutions that are discharged from hydrothermal springs.

Hydrothermal systems

Hydrothermal activity in the form of hot springs, geysers, fumaroles and seepage through sediments and lavas on the seafloor is a common feature along plate margins in tectonic belts. Intermittent hydrothermal discharge may precede or overlap periods of volcanic activity during the development of tectonic systems. Hot water and thermal emanations discharged on the seabed are part of convection circulation of seawater in the oceanic crust. This involves the penetration of seawater through fractures and pore spaces in several kilometres of rock below the seabed, heating of the water and rock adjacent to magma and heat sources deep in the tectonic ridge structures, and its rise and discharge from fissures, faults and vents on the seabed. In the course of this circulation the seawater dissolves metals and mineral constituents from the rocks through which it passes and along with additional fluids and metals from magmatic sources, is discharged from vents and fractures on the seafloor at temperatures as high as 400° C. These high temperature fluids usually contain metals and ions in solution, and in colloidal or other fine particles, and on mixing with colder seawater appear as black or white smoky coloured geysers and plumes, or

they emerge as seepage springs in the sediments and lavas on the seafloor.

Occurrences of metalliferous sediment shown on Map 1659A are related directly to past or present hydrothermal sources. Hydrothermal activity is considered to be a major primary source for the metal constituents in metalliferous sediments. Other less important sources for the metals are sediment derived from land masses, elements carried in solution in seawater, and elements that are leached from seabed sediments and volcanic rocks, transported, and redeposited by diagenetic processes. Metalliferous sediments appear to have a very complex history and all three processes, hydrothermal effusive, hydrogenous, and diagenetic, may be interrelated to some extent in their development.

Aside from the deposition of metalliferous sediments and crusts on the seafloor, hydrothermal systems may deposit metals in veins, fractures and pore spaces in the bedrock below vents and discharge areas in a hydrothermal field. Evidence of such processes producing alteration of bedrock and deposition of metallic minerals is found in many ancient mineral deposits and at a number of sites on the seafloor where mineral stockworks and alteration zones are forming at the present time.

The hydrothermal effusive processes referred to in this brief introduction are illustrated in the descriptions of some of the recently discovered hydrothermal fields on the seafloor, and the metalliferous sediments and other mineral occurrences developed by them. Hydrothermal effusive and volcanic exhalation concepts have been applied for more than a century in genetic models for manganese nodules and iron-formation (Berger, 1986). The processes now being observed on the seabed are proving to be very similar to those visualized or anticipated previously (Gross, 1965). Recent technological advances in remote sensing and manned or remotely controlled submersible craft have made it possible to explore active hydrothermal systems on the seafloor and to undertake quantitative study of processes that form major mineral deposits.

MANGANESE NODULES AND CRUSTS

Manganese nodules were dredged by the *HMS Challenger* Expedition in the Pacific Ocean in 1872-76. (Murray, 1878; Murray and Irvine, 1895; Murray and Renard, 1891). The widespread distribution of manganese nodules and crusts on the deep parts of the ocean floor shown on Map 1659A is based on information from drill cores, dredged samples, seabed photos, video camera records and direct observation from submersibles.

The nodules are composed mainly of manganese and iron oxide and range from micro-sized particles to potato-sized concretions that contain small amounts of nickel, copper, cobalt, molybdenum, platinum and other metals.

Manganese-rich crusts similar in composition to the nodules are found in some areas and range from coatings and veneers a few millimetres thick to layered crusts that are several centimetres thick. They are deposited on sand grains, pebbles, rock fragments and bedrock, or blanket unconsolidated sediments. (Mero,1965; Glasby, 1977).

Depositional environments

Manganese nodules and crusts occur in many different environments including freshwater lakes, fiords, continental shelves, seamounts or abyssal plains and basins. The most extensive nodule fields are Mesozoic or younger in age and nodules are forming at a slow rate at the present time. Nodules with interesting nickel and copper content are found in some of the deep ocean basins at depths of 4000 to 5000 metres. They appear to be related to active tectonic belts and are found chiefly below the carbonate compensation depth in areas with low clastic sedimentation and high biological activity in overlying surface waters (Cronan, 1980, p.140).

The development and distribution of nodules are influenced by a variety of regional and local factors that include: the size, morphology, internal features, mineralogy, age and rate of growth; the availability, size and composition of nuclei; bathymetry or paleobathymetry; carbonate compensation depth; seawater composition; bottom currents and paleocurrents; seabed topography; redox potential at the sediment-water interface; composition, thickness and age of underlying sediments; thermal gradients in the sediment column; rates of detrital or chemical sedimentation, and biological productivity in the water column; bottom organisms; and proximity to volcanic, hydrothermal-effusive and tectonic activity. Lack of detailed systematic sampling of nodules in all of the environments in which they occur has limited research and understanding of the respective role and interrelationship of these factors (Cronan,1980; Eldersfield,1977).

The source of metals in the nodules is attributed to the following processes singularly or in combinations: discharge of hydrothermal solutions along active tectonic belts; leaching of metals from the bottom sediments and volcanic rocks during diagenesis and consolidation, and subsequent transport and deposition by interstitial water; solution and transport of metals by seawater with precipitation at favorable sites; and deposition of metal-bearing clastic or colloidal sediment derived from a landmass (Greenslate, et al. 1973: Glasby,1977; Calvert,1978).

Interrelated environmental factors which control the deposition and concentration of nickel- and copper-bearing nodules that are of significance as resources are found:

a) below the carbonate compensation depth in abyssal areas isolated from the deposition of continental clastic detrital material, where sedimentation rates are low and bottom sediments commonly consist of siliceous ooze or red clay;

b) in proximity to active spreading ridges, major fracture systems, and active volcanism that provide sources of metals and nuclei for nodule growth;

c) where bottom currents are effective in transporting

metals in solution and supplying oxygenated water conducive to the precipitation of metals and in promoting the growth of nodules by inhibiting sedimentation;
d) in areas of high biological productivity, where metals are collected from the seawater by organisms and contributed to the pelagic sediments.

The size, shape, mineralogy, physical and chemical properties, and distribution of nodules are highly variable, on both broad and local scales reflecting the complex interplay of environmental factors and the dominant role of one or two genetic processes.

Physical and chemical properties of nodules

Manganese nodules are commonly spheroidal to ellipsoidal, botryoidal, discoidal, tabular or faceted in shape and vary from 2 to 5 cm in their greatest dimension. They range from micronodules that are less than one millimetre to large irregular or spheroidal masses one metre in diameter and weighing nearly a tonne. Many nodules are formed around a nucleus consisting of nodule, rock or mineral fragments, or biological remains, which include basalt, sediment, palagonite, tuff, pumice, glass, clay, volcanic clasts, calcareous phosphate, zeolite, sharks teeth, fish bones, foraminifera tests, spicules and metal debris. Nuclei in some cases appear to have influenced the shape of the nodule especially in the early stages of growth. (Raab and Meylan, 1977)

Internal textures and structures of nodules vary from concentrically layered to massive with microlaminae forming uniform layers or arcuate cusps from 0.25 to 10 μm in thickness. Textures range from granular, globular, dendritic, acicular, to radial crystal habits and growth (Sorem and Fewkes, 1977).

The rate of growth of manganese nodules is very slow. A median rate of 5 mm in one million years is much slower than the rate of accumulation for Pacific pelagic sediments which is in the order of two metres in one million years. Nodules with a high Mn/Fe ratio appear to grow much faster and growth rates may range from one millimetre to greater than 50 mm in a million years (Ku,1977; Cronan,1980,p.121; Calvert,1978).

Nodules are commonly earthy black, bluish-black, or deep brown with a dull vitreous lustre, and are composed of highly porous, fine grained crystalline aggregates, colloidal-size particles and amorphous materials. Their hardness ranges from 1 to 4 on the Mohs scale of 10 and averages about 3. Some are tough and durable but most deep water nodules and those containing less than 2 to 3 per cent calcium carbonate are brittle and friable. Their density averages 1.95 grams per cubic centimetre; porosity ranges from 55.2 to 62.6 per cent with a mean value of 58.3 per cent; and pore diameter averages 7 nm. The dry bulk density of nodules ranges from 1.22 to 1.65. (Meyer,1973; Halbach et al., 1975; Greenslate,1977)

Mineralogy of nodules

Nodules consist predominantly of amorphous and very fine grained hydrated manganese and iron oxide minerals with variable amounts of silica, carbonate, and detrital and biological materials. The major mineral phases of iron and manganese oxides control the uptake and retention in the nodules of minor elements such as nickel, copper, cobalt, molybdenum and rare earths. Identification of specific mineral phases is difficult because of the intimate intergrowth of the different mineral phases and associated detrital material.

Of the large number of complex hydrous manganese oxide mineral phases indentified in the nodules, todorokite (1 nm phase) and birnessite (0.7 nm phase), are the most common and are associated with disordered birnessite (γMnO_2), ramsdellite (MnO_2), nsutite(Mn^{2+}, Mn^{4+}) $(OH)_2$, psilomelane (Ba, K, $MnCO)_2$ Mn_5O_{10}, xH_2O, hollandite and others. Iron associated with the manganese minerals is present in goethite $Fe(OH)_2$, lepidocrocite (FeOOH), hematite (Fe_2O_3), maghemite (γFe_2O_3), amorphous hydrated ferric iron oxide gel, colloidal ferric iron species and hydrated ferric oxide polymer. In addition to the iron and manganese minerals nodules contain a variety of nonmetallic minerals, amorphous material and biological debris. Clay minerals, quartz, feldspar and chlorite, mostly of detrital origin along with silica gels, chalcedony, calcareous and phosphatic components may be present in varied proportions. Most of these nonmetallic constituents are insoluble in hydrochloric acid and may comprise 25 per cent of the bulk weight of the nodule and contain little, if any of the metals of economic interest. The proportions of different minerals in nodules appear to vary considerably from location to location. Correlations of the distribution of mineral phases with general environmental factors have not been fully documented. (Burns and Burns,1977).

Chemical composition of nodules

Aside from water and volatile content, the major elements in nodules are oxygen, manganese, iron, silica, and lesser amounts of aluminum, calcium, sodium, and magnesium and a host of minor or trace elements of which nickel, copper, and cobalt are of greatest interest. The amounts and proportions of constituents may vary considerably within single nodules, in different sizes of nodules, and in nodules from different regions and different oceans. (Calvert,1978; Haynes et al.,1985).

The average abundance of some of the elements in manganese nodules and other iron-manganese oxide deposits from the world oceans reported by Cronan (1977) are in weight per cent: Na-1.94, Mg-1.82, Al-3.09, Si-8.62, P-0.22, K-0.64, Ca-2.53, Ti-0.64, V-0.05, Cr-0.0014, Mn-16.17, Fe-15.00, Co-0.29, Ni-0.48, Cu-0.25, Zn-0.07, Sr-0.08, Y-0.031, Mn-0.04, Ba-0.20, Pb-0.08, Bi-0.0008, Zr-0.06.

Table 1. Average composition of abyssal nodules and encrustations from the Atlantic, Pacific and Indian Oceans

Average content (in weight per cent)	Atlantic Ocean	Pacific Ocean	Indian Ocean
Manganese	15.46	19.27	15.25
Iron	23.01	11.79	13.35
Nickel	0.308	0.846	0.534
Copper	0.141	0.706	0.295
Cobalt	0.23410	0.290	0.247
Manganese/Iron	0.67	1.63	1.14

The average composition of abyssal nodules and encrustations from the Atlantic, Pacific and Indian Oceans are shown in Table 1 (Cronan,1977).
Representative samples of nodules from the North Pacific area containing higher metal content reported by Mero (1977) have an average weight per cent of manganese of 28.8, iron 7.3, cobalt 0.29, nickel 1.71, and copper 1.52.

Relative to seawater or average crustal rocks, nodules are enriched in Mn, Fe, Ni, Cu, Co, Zn, Mo, Ba and Pb. Cronan (1977) has assembled data on a world basis on the composition and inter-element relationships of nodules that have been grouped according to seven different environments (Table 2).

The Mn/Fe ratios derived from these data are higher in the Pacific Ocean, intermediate in the Indian Ocean and lowest in the Atlantic Ocean. Mn/Fe ratios in nodules from the deeper ocean basins vary from 3.94 to 0.67 but ratios for shallow marine and continental margin nodules are more variable, ranging from as high as 28.8 to less than 1.0. The possibility exists of finding nodule deposits near the continents with Mn/Fe ratios of 3 to 6 and a low content of nickel, copper and cobalt that could be considered as resources of manganese.

The Mn/Fe ratio in nodules from a high grade region of the North Pacific is higher than that for average abyssal Pacific nodules, 3.94 compared with 1.63. The ratio between these two metals may be indicative of environmental influences such as volcanic or tectonic activity, terrigenous input, or sedimentation rates.

The average contents of Ni, Co, and Cu are consistently higher in nodules from the Pacific Ocean, intermediate in those from the Indian Ocean and lowest in nodules from the Atlantic Ocean. Exceptions are that the content of cobalt is higher in Mid-Atlantic Ridge than in Carlsberg Ridge nodules in the Indian Ocean, and copper content is higher in the Blake Plateau than in the Campbell Plateau nodules.

Ni/Cu ratios for average and abyssal nodules are lowest in the Pacific, intermediate in the Indian and highest in the Atlantic Ocean but the trend is reversed for seamount, plateau and ridge nodules.

Distribution of manganese nodules

Nodules bearing appreciable amounts of nickel, copper and cobalt are distributed in quantity in a belt within 30° of the equator in the Pacific and Indian oceans and in a large region of the south, central and southeastern Pacific.

A region of special economic interest where sample data and information on nodules are most extensive lies in the central northeast Pacific Ocean, bounded by latitude 5°N and 25°N and longitude 110°W to 155°W. This region covers the Clipperton and Clarion fracture zones. The bottom sediments are siliceous ooze and red clay and concentrations of nodules have a combined content of nickel and copper in excess of 3 per cent. Concentrations of nodules are more consistent than in most other areas, ranging up to 30 kg/m^2, but nodule abundance varies considerably within local areas (Hayes et al.,1985; Frazer,1977).

A large area in the Central Pacific Ocean north of 30°N has widespread concentrations of nodules but no samples indicate values high enough to be considered for mining. Nodules with a metal content that might be high enough for mining have been sampled at a number of locations southwest of Hawaii within an area 5°N to 10°N and 170°W to 175°W but concentrations of nodules appear to be low.

Nodules bearing a high content of nickel and copper might be expected to occur south of the equator at the southern edge of the equatorial zone of high organic productivity with the distribution pattern of the northern belt reflected in the south. Because of a number of factors including depth of water and sedimentation rates, the pattern of nodule distribution seen in the north is not found in the south and large concentrations of high grade nodules are not reported (Halbach,1983). Nodules with

Table 2. Average abundance of Mn, Fe, Ni, Co and Cu in manganese nodules and crusts from different environments (in weight per cent) (Cronan 1977)

	Seamounts	Plateaus	Active ridge	Other ridge	Continent border	Marginal seamount	Abyssal nodules
Mn	14.62	17.17	15.15	19.74	38.69	15.65	16.78
Fe	15.81	11.81	19.15	20.08	1.34	19.32	17.27
Ni	0.351	0.641	0.306	0.336	0.121	0.296	0.540
Co	1.15	0.347	0.400	0.570	0.011	0.419	0.256
Cu	0.058	0.087	0.081	0.052	0.082	0.078	0.370
Mn/Fe	0.92	1.53	0.80	0.98	28.8	0.81	0.97
Depth (m)	1872	945	2870	1678	3547	1694	4460

high nickel and copper values are found in the southern equatorial belt at the edge of the calcareous zone between 85°W and 105°W and 125°W and 140°W but nodule occurrences are apparently infrequent throughout much of the area except in the broad zone between the East Pacific Rise and South America where high metal content and high concentrations of nodules are reported.

Manganese nodules with nickel and copper content above the cutoff limits are concentrated in an area in the Indian Ocean that extends from 10°S to 25°S and 70°E to 86°E. (Frazer and Wilson,1980).

Another large area southwest of Australia has scattered concentrations of nodules but the metal content determined from a limited number of analyses appears to be generally low. (Cronan,1980; Haynes et al.,1985).

Nodules are sparsely and irregularly distributed through broad areas of the Atlantic and probably the most interesting concentrations are found on the Blake Plateau east of Florida where nodules and crusts with Mn/Fe ratios favourable for use as a manganese resource occur in shallow water (Manheim,1972).

Nodules on the bed of the Tyrrhenian Sea off the west coast of Italy are of special interest for the same reasons. There appear to be good possibilities for finding nodules in other areas near continental margins where they have high Mn/Fe ratios and could provide resources of manganese (Cronan,1980; Glasby,1977).

An area south and southwest of the African continent may also be of economic interest.

Sample data for the nodule bearing regions referred to are very limited and inadequate for classifying specific mineral resource areas or for delineating areas of little significance.

Estimates of manganese nodule resources

The mineralogy, composition and origin of manganese nodules are described in a voluminous literature but assessments of their resource potential are not well documented. Potential resources of copper, nickel and cobalt in manganese nodules were investigated during the 1960s and 1970s and results of this work have been summarized in Volume 1 of the United Nations Seabed Mineral Series. Most of the estimates of resource potential were based on a minimum abundance of 10 kg/m^2 and a minimum combined grade of 1.76 per cent copper and nickel which were considered necessary for a viable mine site. Estimates of potential worldwide resources of nodules on this basis range from 14 to 99 billion tonnes. The Clarion-Clipperton zone in the East Pacific with estimates of 8 to 15 billion tonnes was the main area of interest.

Estimates of resource potential in manganese nodules and crusts vary greatly. Mero (1977) states that within the North Pacific high-grade area, assuming an average concentration of 9 kg/m^2 of ocean floor over 6 million km^2, a resource of about 38 billion tonnes of dry nodules averaging 29 % Mn, 0.3 % Co, 1.77 % Ni and 1.4 % Cu would be indicated. The water content of the nodules is assumed to be 30 %. Such a resource would contain about 11.0 billion tonnes of manganese, 115 million tonnes of cobalt, 650 million tonnes of nickel, and 520 million tonnes of copper. Nodules in this area have an average content of about 0.14 % Zn and 0.06 % Mo, and might be considered as a source of these two metals as well.

COBALT IN MANGANESE-IRON CRUSTS

Cobalt-rich manganese crusts are widely distributed on the slopes of seamounts and islands in the equatorial Pacific, on the Blake Plateau in the northwest Atlantic, and with denser concentrations of nodules in many parts of the ocean basins. Research by Cronan (1983, 1985); Halbach (1983); Halbach and Manheim (1984); and Manheim (1986) indicates that the main factors controlling distribution of cobalt-rich manganese crusts in the Central Pacific are;

1) elevated biological activity and extraction of cobalt from seawater by organisms;
2) water depths less than 2000 metres in the vicinity of seamounts;
3) manganese enrichment at certain ocean depths related to zones of minimum oxygen;
4) low rates or absence of turbidite sedimentation.

Exploration shows that the most favourable areas for cobalt-bearing crusts lie on seamounts older than 25 Ma, within water depths of 800 to 2400 m, from 5° to 15° from the equatorial zone and in areas where two generations of crusts with ages from 16 to 9 Ma and 8 Ma or younger are present (Clark et al., 1985; 1984). Cobalt concentrations in manganese-iron crusts and nodules in the Mid-Pacific Mountain and Line Islands area increase from less than 0.4 % at water depths of 4000 m to 1.2 % on seamount slopes and summits less than 2500 m in depth. The thickness of crusts ranges from 2 cm in the upper slope areas to 9 cm in the lower areas and may contain more than 16 kg (equivalent dry weight) of crustal material per square metre of crustal surface (Halbach and Manheim, 1984).

The composition of the crusts varies greatly with 15 to 31 % manganese, 7 to 18 % iron, and Mn/Fe ratios from 1.0 to 3.4. Cobalt content as high as 2 % was found in samples from summit areas less than 1500 m in depth, and the average content in all samples was 0.8 %. The crusts contain significant amounts of nickel, lead, cerium, molybdenum, vanadium and other minor metals (Manheim,1986). Clark et al., (1985) report that the crusts contain 80 times more platinum than the upper continental crust with maximum amounts in crusts at water depths of 1100 to 1250 m. Platinum content ranges from 0.6 ppm in the older crusts to 0.3 ppm in younger crusts and varies directly with the amount of cobalt and nickel.

Manheim (1986) lists important areas in the Pacific where cobalt-bearing manganese crusts have been explored. These include the Northwest Hawaiian Ridge,

Johnston Island, Howland-Baker Islands, Marianas Island, Guam, Marshall Islands, Central Seamounts, Palmyra-Kingman, Micronesia and Wake Island. Cronan (1983) pointed out that conditions are favourable for the formation of cobalt bearing crusts in the Central Pacific Basin west of the Southern Line Islands, east of Phoenix Islands, northwest of the Phoenix Islands, and in the North Penhryn Basin north of the Penhryn Islands and in a number of other areas, east of the Gilbert Islands, south of Phoenix Islands, South Penhryn Basin, Gilbert Islands, Samoa and Northern Cook Islands.

The average metal content in crust samples from the Hawaiian Archipelago and Johnston-Palmyra Region in the Pacific reported by Clark et al. (1984), is 0.90 % cobalt, 0.50 % nickel, 0.06 % copper, and 24.7 % manganese. The average thickness of the crusts is 2.4 to 2.8 cm, the growth rate ranges from 4.8 mm/Ma for the older crusts to 2.7 mm/Ma for the younger, and the older crusts probably formed between 16 and 9 Ma ago (Clark et al., 1985). Resource estimates for the cobalt-rich manganese crust potential in the Exclusive Economic Zones of the United States Trust and Affiliated Territories in the Pacific are based on maximum crust thicknesses of 1.0 to 2.5 cm, an average dry density of 1.33 g/cc and cobalt content ranging from 0.78 % to 1.18 %, nickel content from 0.39 to 0.53 %, manganese from 21.4 to 26.56 %, and platinum content from 0.6 ppm in the older crusts to 0.3 ppm in the younger crusts. The area around the federated States of Micronesia and the Marshall Islands appear to have a much larger resource potential for cobalt, nickel, manganese and platinum than other island areas studied (Clark et al., 1985).

In the Atlantic Ocean cobalt bearing manganese-iron crusts cover thousands of square kilometres on Blake Plateau. Other areas on the Sierra Leone Rise, and the east flank of the Mid-Atlantic Ridge have crusts with a cobalt content approaching one per cent. The mean content of cobalt in 77 samples of crusts from depths to 2500 m in the Atlantic Ocean is 0.5 % and the total content ranges from 0.5 to 0.85%, while the mean content of manganese is 20.15% and the total ranges from 17.9 to 22.28 % (Manheim,1986).

MINERAL OCCURRENCES IN THE MEDITERRANEAN SEA AND RED SEA

Santorini Island, (Thera), Aegean Sea
MN-1 * 36°26'N 25°30'E

Submarine hydrothermal activity and mineral deposition related to volcanic activity was observed offshore from Santorini Island as early as 1650 and has been studied at various times since. Iron-rich sediments are now forming in several bays on the Kameni Islands within the Santorini Caldera by precipitation from warm submarine springs which represent a late phase of volcanic activity.

* Map numbers on Map 1659A.

Cores of layered metalliferous sediment up to 3 m thick taken from one bay contain about 33% Fe_2O_3, from 20 to 65 % SiO_2, 2 to 4 % CaO and MgO, 2 to 10 % Na_2O and K_2O, and minor amounts of many other metal constituents. The gel-like silica-rich material is not homogeneous but contains considerable rock detritus and varies from ferric hydroxide in the upper parts to ferrous carbonate, ferrous hydroxide, basic sulphate, ferrous silicate gel, and ferrous sulphide formed locally by the activity of sulphate reducing bacteria (Puchelt, 1973). The content of iron, copper, lead, scandium, and molybdenum in the sediment decreases outward from the exhalative zone and the content of zinc, manganese, vanadium, and chromium increases from the inner to the outer exhalative zone (Smith and Cronan,1983).

The Santorini Islands are located on the Aegean Plate on part of an island arc between Greece and Turkey associated with the subduction of the African Plate beneath the Aegean Plate (Bostrom and Widenfalk, 1984). The metalliferous muds deposited by hydrothermal effusive activity off the Santorini Islands undoubtedly represent the sedimentary progenitor of an Algoma type iron-formation (Gross, 1965, 1983) and genetic processes leading to the deposition of these chemical sediments are clearly demonstrated at this site.

Volcano Island, Tyrrhenian Sea.
MN-2 38.5°N 15°E

Volcano Island is the southernmost island of the Eolian Archipelago in the Tyrrhenian Sea between Italy and Sicily. Fumarolic activity is asociated with La Fossa, an active volcano in the northern part of the island and extensive hydrothermal effusive activity is found in the Baia di Levante adjacent to three volcanic islands, Volcano, Vulcanello, and Faraglione. Trachytic tuff from the last volcanic eruption in 1890 that covers the floor of the bay is being mineralized by hydrothermal springs. Pyrite and marcasite, alunite, opal and sulphur cement the grains of volcanic sand and tuff and the silicate minerals are replaced by opal and the titaniferous magnetite grains by iron sulphide. Extensive amounts of iron sulphide have been deposited by the hydrothermal solutions as framboidal pyrite and the rocks are enriched in iron, silica, sulphur, boron and barium. Colloform crusts of goethite have formed by oxidation of the sulphide minerals and by primary deposition of iron oxides around the fumarolic vents.

An area of 45 000 m^2 around the hydrothermal field in the Baia di Lavante is covered by a 40-cm-thick layer of sulphidized sand with the lower half containing more sulphide minerals than the upper part. Sulphidized sand beds are more than 6 m thick in the subaerial part of an isthmus between two of the volcanoes. The sulphide-rich sediments contain up to 21% iron sulphide and significant amounts of As, Hg, Bi, Te, etc., that were derived presumably from the hydrothermal waters. Temperatures of the fumarolic water range from 210° C in the La Fossa crater to about 100° C in Baia di Levante. Samples containing 10% or more goethite were dredged from the

outer zones around fumaroles and on the lower parts of the slopes of the volcano (Honnorez et al., 1973).

In a study of the marine environment around Volcano Island Valette-Silver (1981) refers to the role of hydrothermal emissions and the formation of two types of facies. The first is a sulphide facies that includes pyrite, marcasite, chalcopyrite, sulphur, gypsum, anhydrite, iron and manganese oxides, and clay minerals in a shallow marine environment. The second is an oxide mineral facies with sulphates, iron and manganese oxides and hydroxides, and clay minerals produced by the reaction of the submarine hotsprings with seawater.

Palinuro Seamount, Tyrrhenian Sea
MN-3 39°10'N 14°20'E

Copper bearing sulphide minerals mixed with metalliferous ooze have been recovered from craters in Palinuro Seamount, a volcanic edifice in the northeastern part of the Aeolian island arc in the Tyrrhenian Sea. Samples consisting of luzonite and tennantite-tetrahedrite copper bearing minerals are part of indurated sulphide crusts formed at the sediment-seawater interface that are mixed with ooze of organic and volcanic origin. Other minerals found in the samples are native copper and silver, bismuthinite and stibnite, associated with predominant amounts of pyrite and barite. The sulphide minerals are believed to have a volcanogenic exhalative origin (Minniti et al., 1984)

Tyrrhenian Sea manganese nodules

An ancient basin in the Tyrrhenian Sea with depths up to 4000 m contains more than 20 submarine volcanoes. Deposits of manganese nodules, about 1 cm in diameter, and containing 41 % manganese are found on the seabed in the relatively shallow water (100m) between volcanoes. Nodules are present in quantities of 2-3 kg/m^2 and their distribtion throughout this area is not known (Mining Journal, 1982).

Red Sea graben
Area 20° to 25°N and 35° to 40° E
MN-4 22°30'N 37°30'E Atlantis II Deep

Detection of hot brines on the floor of the Red Sea by scientists aboard the RRS *Discovery* in 1964 and the subsequent location of more than 20 deep basins containing hot brines and metalliferous sediment deposits was an important milestone in the exploration of seafloor mineral deposits and for metallogeny in general . The Red Sea graben is 2000 km long and 300 km wide and trends N 35° W. It was formed during arching and thinning of the continental lithosphere between the Nubian and Arabian shields. Spreading began along the rift fracture system during Late Eocene time. The rifting was accompanied by reef building, the deposition of cherts, conglomerate, sandstone, shale, salt, anhydrite, diatomite, and limestone, and extrusion of basalt. Intermittent hydrothermal effusion along the axial part of the trench has led to the deposition of metalliferous sediments over the last 25 000 years.

The shallow marginal areas of the Red Sea are usually less than 1000 m deep and are separated by the narrow deep axial zone that is divided into three segments. The southern segment north of 16° N resembles an oceanic rift. The middle segment from 19°30'N to 23°50'N comprises 15 axial "deeps" up to several kilometres in length that contain hot and cold brine layers located above soft, fine-grained metalliferous muds. The northern segment has less relief and rarely exceeds 1500 m in depth (Pautot et al., 1984).

A wealth of scientific information on the origin of metalliferous sediments has been acquired during exploration of the deposits. A potential resource of copper, zinc, lead, gold, and silver has been delineated in the Atlantis II Deep on the axis of the rift system west of Jeddah, Saudi Arabia. Only a brief statement can be given here summarizing some of the available information.

The Atlantis II Deep is a local tectonic depression in the Middle segment within the active rift zone where the spreading rate is 2 to 3 cm/a. The Deep is filled with stratified hot brine to a depth of 2000 m. The brine overlies complexly layered metalliferous chemical sediment that is 5 to 30 m thick. The thin, layered (1 mm to 20 cm) multicoloured stratigraphic units appear to be undisturbed over an area of 65 km^2 except in the southwest part of the Deep where beds are disrupted, deformed and brecciated by new hotsprings venting through earlier deposited metalliferous mud. (Shanks, 1982).

Lithostratigraphy of the metalliferous chemical sediment in the southwest part of the basin described in the work of Backer and Richter(1973), Bischoff (1969), and Oudin et al.,(1984), indicates that basal basalt flows are overlain by massive beds 3 m thick of finely crystalline hematite and limonite that contain 20% or more detrital particles, fine grained crystalline iron sulphide and sulphate minerals. The upper unit is approximately 8 m thick and is divided into three parts. The first, about 4 m thick, consists of sulphide and silicate facies and is characterized by a transition at the base from anhydrite and gypsum beds to hematite lenses that grade into goethite layers. The second part, 2 m or more in thickness, consists of interlayered oxide-, silicate- and sulphide-rich facies that are brecciated in places and fragments of sedimentary hematite that are cemented by sulphide and silicate material. The third part, about one metre thick, is semiliquid and consists of amorphous sulphide and silicate layers. The upper unit of chemical sediment throughout Atlantis II Deep is 3 to 4 m thick and consists mainly of amorphous silicates and minor sulphidic mud, iron-rich montmorillonite clay facies and layers of lepidocrocite (hydrated iron oxide).

The metalliferous sediments exhibit vertical variation in the composition and distribution of mineral phases which may be due to element migration, external contribution of mineral constituents and diagenetic processes.

Carbonate minerals make up thick layers and are characterized as separate facies. Sulphate-sulphide, sulphate-oxide, sulphate-carbonate and carbonate-sulphide facies formed during deposition or after burial. Manganese appears to be mostly concentrated in manganosiderite and manganite. Zinc and copper are present in sphalerite and chalcopyrite in the lower sulphide facies but mineral phases containing these elements were not detected in other facies (Durga Prasada Rao et al.,1984).

Metalliferous sediment precipitated in the Atlantis II Deep consists mainly of finely laminated iron and manganese oxide facies with interlayered and disseminated sulphide facies. In the southwest part of the basin the unlithified beds are disturbed and cut by veins formed by late stage hydrothermal venting through the layered sediment. The three processes contributing to the deposition of this metalliferous stratafer (Gross,1986) sediment are detrital sedimentation, chemical precipitation, and epigenetic mineral deposition. Cavities in the sediment are lined by epigenetic sulphide minerals and vein mineralogy is dominated by anhydrite, talc, smectite, pyrite, sphalerite, and chalcopyrite. Talc and magnesium-rich smectites dominate deep veins whereas more iron-rich smectite and anhydrite dominate veins nearer the sediment-water interface. Metalliferous sediment in parts of the southwest basin has been recrystaliized locally to a hematite-magnetite-pyroxene assemblage which probably was caused by the intrusion of basalt into the metalliferous sediment (Zierenberg and Shanks, 1983).

The Atlantis II Deep contains the largest and most important concentration of metals in the Red Sea graben. The deposit consists of layered unconsolidated siliceous chemical sediments rich in iron, manganese and sulphide minerals; these are about 10 m thick and distributed over an area of 5 by 13 km at depths of 2000 to 2200 m. The deposit contains more than 32 million tonnes of metals including 0.4 Mt or 1.3% copper (dry weight), 1.7 Mt or 3.4% zinc, 0.1% lead, 29% iron, 54 ppm or 5000 tonnes of silver, 0.5 ppm gold, and some cobalt (Shanks, 1982).

Plans for mining this deposit are well advanced. Production is planned at the rate of 2 600 000 tonnes per year to provide 90 000 tonnes of concentrate containing 32% zinc and proportional amounts of copper, silver and gold (Amann, 1985; Degens and Ross, 1969).

MINERAL OCCURRENCES IN THE INDIAN OCEAN

Gulf of Aden
MN-5 12°35'N 47°39.9'E Water depth 2260 m.

Hydrothermal metalliferous sediment material attached to pieces of basalt lava was dredged from the edge of the median valley in the Gulf of Aden. The sediment consists of two main components, manganese oxide in the form of spongy brown to hard black lumps and coatings, and friable green massive smectite. The samples dredged were composed of basalt lava, hard and soft ferromanganese oxide, yellow to green friable material, orange powdery iron oxide, and soft chocolate brown material. Smaller amounts of an iron-oxide component are mixed with the manganese oxide and smectite but sulphide material was not found. The iron-manganese component contains 35 to 45% manganese, up to 6% iron and 15% silica. Mixtures of smectite mud and iron and manganese oxide contained about 22% iron, up to 10% manganese and 20 to 25% silica. All of the material contained 4 to 5% sodium and potassium (Cann et al.,1977).

Owen Fracture Zone
MN-6 9°50'N 57°57'E

Manganese oxide coatings about 5 mm thick found on samples of fresh glass and basalt are believed to indicate hydrothermal activity along this fracture system (Rona et al., 1981).

Carlsberg Ridge
MN-7 01°40'S 67°46'E

Fragments of pillowed and flow basalts have coatings of manganese oxide 5 mm thick that suggest hydrothermal activity in the area (Rona et al., 1981).

Vitiaz Fracture Zone
MN-8 5°21'S 68°37'E

Disseminated and vein sulphide was found in samples recovered from an area at the intersection of the rift valley and the Vitias fracture zone (Rona et al.,1981).

DSDP Hole 236
MN-9 01°40.6'S 57°39'E

Basal sediments from this hole contain 28 % iron and are believed to be of hydrothermal origin (Cronan,1980).

Amirante Passage, North of Madagascar Island
MN-10 9°34.3'S 52°27.7'E

Pieces of pink chalk heavily encrusted with manganese oxides, manganese oxide crust, and manganese nodules 2.5 to 4 cm in diameter were recovered from a depth of 3700 m by the drill (Masson et al., 1982).

LSDA 120G
MN-11 24°30'S 57°29'E
DODO 110PG
MN-12 21°31'S 78°01'E

Cores of bottom sediments obtained by expeditions from Scripps Institute of Oceanography at the above sites contain 6 per cent or more iron as iron oxide and some manganese oxide (Boström et al., 1969).

Ninety East Ridge, DSDP Hole 215
MN-13 8°07.30'S 86°47.50'E

Two metres of iron-oxide rich sediment overlies fresh pillow basalt and is overlain by Eocene to mid-Paleocene

calcareous nannofossil ooze from 149 to 151 metres in DSDP Hole 215 that was drilled at a water depth of 5319 m (von der Borch et al., 1974).

Wharton Basin, DSDP Hole 213
MN-14 10°12.71'S 93°53.77'E

Zeolitic clay grades to nannofossil-bearing manganese iron-oxide rich clay of Middle Miocene age from depths of 70 to 135 m in DSDP Hole 213. An iron-oxide manganese-rich facies was intersected from 147 to 152 m in the hole which overlies "weathered" or altered basalt. The hole was drilled at a water depth of 5611 m (von der Borch et al., 1974).

MINERAL OCCURRENCES IN THE NORTH ATLANTIC

DSDP Hole 112
MN-15 54°01'N 46°36'W

Basal metalliferous sediment was intersected in DSDP Hole 112 at a depth of 3657 m in the south Labrador Sea near Basement Ridge (Laughton et al., 1972).

DSDP Holes 114 and 117A
MN-16 60°N 27°40'W
MN-17 56°N 15°W

Basal metalliferous sediment containing more than 9% iron and a significantly high content of manganese, copper and zinc was intersected in DSDP Holes 114 and 117A (Horowitz and Cronan, 1976).

Western Biscay Abyssal Plain
MN-18 45°02.65'N 9°00.63'W

Basal metalliferous sediment was indicated by Laughton et al.(1972) at a water depth of 4901 m.

DSDP Site 136
MN-19 34°10.13'N 16°18.19'W

313 m of Pliocene to Miocene nannoplankton chalk ooze, barren clay, ash, calcareous red clay and multicoloured clays were penetrated below water depth of 4169 m, in an area of abyssal hills located 900 km southwest of Gibraltar. The writers believe that the multicoloured clay may have a significant component of hydrothermal sediment (Hayes et al., 1972).

DSDP Site 137
MN-20 25°55.53'N 27°03.64'W

This site is about 1000 km west of Cap Blanc, Africa, in an area of abyssal hills at a water depth of 5361 meters. The hole penetrated 40 m of brown clay, black clay, calcareous clay, chert, and marl-chalk ooze. The brown clays and chert may contain metals from hydrothermal sources (Hayes et al., 1972).

DSDP Site 138
MN-21 25°55.37'N 25°33.79'W

This site is about 870 km west of Cap Blanc at the foot of the continental rise at water depths of 5288 metres. The drill penetrated 422 m of sediment including 200 to 250 m of Tertiary clay, silt, and sand, 190 to 240 m of Upper Cretaceous mudstone and shale; and thin layers of chert at 255 m. Clay and dolomite silt are cyclically interbedded with carbonaceous mud and overly fine grained altered alkalic basalt. The chert layers may indicate significant hydrothermal activity in this area in the past (Hayes et al., 1972).

DSDP Site 141
MN-22 19°25.16'N 23°59.91'W

This site is located about 200 km north of the Cape Verde Islands on a diapiric structure in an area of gently rolling abyssal hills at a water depth of 4148 m. The hole penetrated about 80 m of Pleistocene to Pliocene chalk ooze and 200 m of brown, red, and green barren clay of possible hydrothermal origin that rests on highly altered serpentinized basalt at a depth of 295 m (Hayes et al., 1972).

Sommet Seamount, Kane Fracture Zone
MN-23 24°03'N 28°56'W

Metalliferous sediment composed of brown mud, micronodules of manganese and manganese nodules in brown clay was reported at a depth of 5390 m at this site (Latouche et al., 1979).

Central Caldera of Madcap Volcano
MN-24 28°52'N 25°25'W

Six cores from the vicinity of fracture zones or volcanic features at a depth of 4870 m have iron- and manganese-bearing sediments interbedded with calcareous material, brown ooze, and montmorillonite clay that contains fragments of volcanic glass, plagioclase, zeolite, fluorapatite, pyroxene and amphibole as well as manganese nodules and manganese-iron concretions (Latouche et al. 1979).

Median Valley, Mid-Atlantic Ridge
MN-25 45°30'N 27°50'W

Iron-rich sediments containing more than 14% iron in samples from the Median Valley area are enriched in arsenic and mercury and are believed to have been deposited at the ridge crest by hydrothermal activity. Within samples from the Median Valley mercury varies from 308 to 697 ppb, arsenic from 193 to 361 ppm, manganese from 0.47 to 0.86% and iron from 8.7 to 14.1%. Metalliferous constituents in these sediments occur in globules and grains of amorphous iron oxide that are up to 0.05 mm in diameter. High concentrations of Mn, Cu, Cr, Ni, Pb, B, As, Cd, and V are associated with the iron oxides. Iron-rich deposits were found in the crestal region of the Median Valley and less ferruginous metalliferous sedi-

ments were found at a number of locations in the Eastern and Western Crest Mountains (Cronan, 1972).

Eastern Flank, Mid-Atlantic Ridge
MN-26 43°1.8'N to 43°7'N
28°13.5'W to 28°32' W

Manganese is encrusted on basalt boulders and coral fragments dredged from this area along the Eastern Flank of a well developed central rift valley on the Mid-Atlantic Ridge (Phillips et al., 1969).

Famous Area, Mid-Atlantic Ridge
MN-27 36°56'N 33°04'W

Samples from the Transform Fault "A" area consist of two types of material, 1) dark brown iron-manganese concretions composed of todorokite and birnessite, and 2) variegated clay-rich material composed mainly of iron- and silica-rich smectites. Clay-rich alteration material in the basaltic rocks may be produced by hydrothermal processes. Manganese nodules and concretions contain about 15% iron, 41% manganese, and 19% silica. Green and yellow clay-rich hydrothermal muds contain 45 to 32 % SiO_2, 34 to 45 % ferrous iron, and up to 2.5 % MnO and Al_2O_3, with the highest iron, manganese and alumina content in the yellow mud (Hekinian and Fevrier, 1979).

Mid-Atlantic Ridge
37°N

Immiscible sulphide globules were trapped in the glass phase of submarine basalts in this area of the Mid-Atlantic Ridge. The globules constitute less than 0.0022 volume per cent of the rock and range from 11 to 233 um in diameter. Globules in glass containing 0.66 to 1.0 wt % TiO_2 contain 20 to 26 wt % Ni + Cu and have an average atomic Ni/Cu ratio of 1.6. Globules in glass with a TiO_2 content of 1.6 wt % have less than 10 wt % Ni + Cu and the Ni/Cu atomic ratio falls to 0.4 (Czamanske and Moore 1977).

Mount Glooscap, Mid-Atlantic Ridge
36°25'N

Basalts from this area may have special metallogenetic significance. They were sampled using a submersible electric drill on a large peak in the crestal mountains of the Mid-Atlantic Ridge about 16 km west of the AMAR rift valley. The basalt samples are enriched in the lighter fraction of rare earth elements and are believed to come from magma that is more evolved or differentiated than that which produced basalt in the Famous area (Walker, et al., 1984).

TAG Hydrothermal Field, Mid-Atlantic Ridge
MN-28 26°08'N 44°27'W

The TAG Hydrothermal Field, situated between two major fracture zones, the Atlantis at 30°N and the Kane at 24°N, lies on a salient of the east wall of the Mid-Atlantic Ridge where water depths range from 2000 m at the ridge crest to 4000 m at the rift valley floor. The hydrothermal field covers an area of at least 100 km^2 over a block faulted topographic high where closely spaced transform faults intersect linear normal fault segments that are 20 to 40 km long and offset up to 10 km. Hydrothermal discharge is enhanced greatly by the closely spaced faults and fractures in the basalt overlying a thermal centre on this slow-spreading oceanic ridge. The mineralogy of the basalts exposed on the seafloor indicates low-temperature zeolite metamorphic facies.

Manganese oxide crusts containing 40 per cent manganese cover about 10 per cent of the seafloor in the hydrothermal field and are being precipitated at rates of about 2 cm/Ma along faults that are subparallel to the rift valley. The accumulation rates for Fe, Mn, Ni, Co, Cu, and Cr in the thin sediment cover of the field are relatively higher than in other areas of the Mid-Atlantic Ridge and metal to aluminum ratios are average (Rona, 1980).

The following hydrothermal mineral occurrences in the TAG Field are reported by Rona et al.(1976).

MN-28 26°07.6'N 44°40.5'W
Manganese oxide crust, todorokite veins, and smectite mud are associated with palagonite, fresh and altered mafic volcanic rock and glass along a transverse ridge.

26°17.8'N 44°24'W
Smectite mud is associated with serpentinized ultramafic rocks, porphyritic gabbro, altered mafic rock, diabase, greenstone, and pyroxenite rocks along a transverse ridge.

26°15.9'N 45°06.3'W
Manganese oxide crust and smectite mud are associated with weathered basalt along a transverse ridge.

26°09.7'N 44°47.4'W,
Hydrothermal manganese oxide forms the matrix of basalt breccia and crusts on altered basalt, pillow basalt and glass along the southeast wall of a linear segment of the rift valley.

26°08'N 44°45'W
Hydrothermal manganese oxide crusts are associated with pillow basalt, basalt, palagonite, glass and zeolites along the southeast wall of a linear segment of the rift valley.

MN-29 25°27.2'N 44°54.6'W.
Iron oxide veins are present in greenstone and metabasalt and veins of talc and chlorite are cut by zeolite in the vicinity of a transverse fault.

MN-28 26°08'N 44°49'W
A cluster of eleven black smoker hydrothermal vents was discovered at water depths of 3600 to 3700 m on the lower part of the east wall of the rift valley in the slow spreading TAG area of the Mid-Atlantic Ridge (Rona, 1985; Peterson et al., 1970).

Snake Pit Hydrothermal Area,
MN-28 26°08.5'N 44°49.5'W

An active vent field with more than eleven sulphide chimneys, hot "black smokers", and a unique biological community was discovered during a survey of a hydrothermal area at Site 649, about 25 km south of the Kane Fracture Zone. The Snake Pit Hydrothermal Area is located on the western half of a small terrace near the crest of the median valley ridge and covers at least 40 000 m^2. Ten small holes were drilled in a deposit consisting of alternating hard and soft formations composed of Fe, Cu, and Zn sulphide minerals disseminated in a clay matrix with lenses of massive sulphide. The basalt is essentially fresh with rare olivine and plagioclase phenocrysts (Gillis, 1986).

Rona et al. (1986) report that the active hydrothermal field is located on a 10-km segment of the east wall of the rift valley between right-lateral transform faults with offsets of less than 10 km. The walls of a rift valley of this slow-spreading ridge are normally nearly straight and subparallel to the bathymetric axis of the rift valley. The east wall projects westward at the TAG hydrothermal field and the rift valley floor narrows to 3 km from about 6 km. Asymmetric spreading of the seafloor is reported with average rates over 10 years of 1.1 cm/a to the west and 1.3 cm/a to the east. The east wall rises from the rift valley floor at a depth of 4000 m to a depth of about 2000 m in a series of steps formed by fault blocks that are hundreds of metres in horizontal and vertical dimension. A linear zone of hydrothermal activity between depths of 2400 and 3100 m on the east wall is marked by layered deposits of manganese oxide, iron oxide, iron hydroxide and iron silicate, and by anomalous temperatures, helium concentrations and metal enrichment in the water.

The black smokers, massive sulphides and vent biota occur at the junction between the floor and east wall of the rift valley at water depths of 3620 to 3700 m and lie between the previously delineated hydrothermal field located about 3.7 km up slope to the east and the bathymetric axis of the rift valley 1.5 km down slope to the west. The axial high of the rift valley is 2 km up slope to the west.

Compound mounds with concentric inner and outer parts that are elliptical in plan view were delineated at water depths of 3620 to 3675 m and the outer mound lies between 3675 and 3700 m. The inner mound is 250 m wide and the outer mound is 580 m wide along azimuth 020°. The seafloor surrounding the mound is covered by talus composed of cobble to boulder-size angular fragments and pillows of basalt and light tan to red mottled sediment with light patches several centimetres in diameter with associated organisms. The sediments are believed to have formed as hydrothermal precipitates and change in colour from red near the margins of the inner mounds to black adjacent to the black smokers where euhedral pyrite crystals exhibit a spectacular glitter.

Shimmering water emanates from a broad area of fractured rock and water temperatures may be up to 200°C. Increasing amounts of suspended material near the centre of the inner mound includes white flocks that are probably bacterial mats, wisps of white smoke and plumes of slowly rising black smoke that were detected up to 400 m above the seafloor as anomalies in dissolved manganese and suspended matter. The black smokers emanate from fractures in the layered rocks rather than from distinct chimneys and at least 11 black smokers are clustered near the centre of the inner mound.

Hydrothermal precipitates dredged from the inner mound consist of 66 wt % sulphide along with sulphate, oxide, hydroxide, silicate and carbonate materials. The sulphides are classified as two types. The first which includes 93 wt % of the sulphide recovered is composed of spongy-textured intergrowths of yellow pyrite and black sphalerite with irregular layering and cavities that contain 38 wt % iron, 9 % zinc and about 1 % copper. The second type of sulphide occurs in dense curved plates several centimetres thick that show distinct zoning. Thicker zones on the concave side of the plates are composed of chalcopyrite and pyrite and a thinner zone on the convex side of sphalerite that has a yellow to reddish-brown oxidation crust several millimetres thick. Concave surfaces on some of the samples are coated with soft black botryoidal and reddish-brown, fine grained iron and manganese oxide and hydroxide up to 1 cm thick; these sulphide coatings contain 22 to 30 % copper and 1 to 3 % zinc. Sulphate materials occur as coarsely crystalline aggregates of anhydrite with fine crystals of pyrite on surfaces and cavities.

Rona et al. (1986) note that the deposit would weigh 4.5 million tonnes assuming that the inner mound is constructed primarily of hydrothermal precipitates (average density 3.0 g cm^3) and is in the form of a semi-ellipsoid, and that it would be similar in size, shape and structure to ancient sulphide deposits such as the Noranda type.

Broken chimneys and about 35 inactive standing chimneys up to 5 m high that are probably composed of sulphide minerals were formed during recent hydrothermal venting in an area about 2 km northeast of the mound deposit at water depths of 3500 to 3600 m.

Mid Atlantic Ridge
MN-30 23°22.15'N 44°57.15'W

Recent volcanism and extensional tectonic activity has occurred at this site on a linear volcanic ridge that trends obliquely across the inner rift valley floor. There is no discernible cover of biogenic sediments and pillow lavas have lustrous glass rims. A pocket of hydrothermal sediment sits exactly at the topographic crest where the axis of the linear ridge is shallowest over a band of fissures (Kong et al.,1985).

Mid-Atlantic Ridge
MN-31 23°N

A number of large boulders were recovered from a fault scarp on the flanks of the Mid-Atlantic Ridge about 60 km from the spreading axis. The black crystalline manganese-rich boulders associated with basalt consist of pure manganese oxide in the form of todorokite (Thompson et al., 1975).

Vema Fracture Zone

	10°53.7'N	45°17.8'W
MN-32	10°55'N	41°18'W
	10°51.5'N	41°51.5'W
	10°47.5'N	44°45'W
	10°42'N	41°38'W
	10°38'N	42°46'W
MN-33	11°04'N	44°13.5'W
	11°09'N	45°15'W

Samples of manganese crust were recovered from these sites along the north and south walls of the Vema Fracture zone.

The manganese crusts are associated with one or more of the following rock types: altered basalt, basalt breccia, serpentinized peridotite, palagonite breccia, palagonite, glassy basalt, variolitic basalt, metagabbro in greenschist-amphibolite facies, gabbro, uralitized and cataclastic gabbro-norite, diabase, serpentinites, serpentinite-carbonate breccia, rodingites, metabasalt with prehnite veins and pillowed basalt (Rona et al., 1976).

MN-32 10°51'N 41°48'W
Vema Fracture Zone. Samples dredged from depths of 2950 to 3650 m on the north wall of the Vema Fracture Zone along Transverse Valley show stockworks and disseminated sulphide mineral assemblages in altered metabasalt of the zeolite to greenschist metamorphic facies. Sulphide minerals including chalcopyrite, other copper-iron sulphides, pyrite, and pyrrhotite are associated with hydrated copper chloride minerals, copper-iron oxide minerals and iron oxide (Bonatti et al., 1976).

MN-33 11°N to 26°N
Mid-Atlantic Ridge. A section of the ridge about 1700 m long was systematically surveyed where spreading is taking place at a rate of about 2 cm/a. Sections of the ridge are offset by transverse faults at intervals of 75 km and seven hydrothermal sites were found along the east wall where venting of hot water takes place along the linear normal faults (Rona, et al., 1984).

San Pablo Seamount, Kelvin Seamount Group
MN-34 39°N 61°W

Aumento et al.(1968) reported that San Pablo Seamount has the form of a large shield volcano with a terrace at 2926 m and a relatively flat top between 1280 m and 915 m with the shallowest part at 878 m below sealevel. The slopes of the seamount flatten below a depth of 3660 m and grade to the flat ocean floor at a depth of 5300 m. Higher parts of the seamount are truncated by a northwest-trending linear feature. Photos and dredge samples show that a well-bedded ferromanganese sediment that was deposited directly on the lava flows and covers the slopes of this seamount.

Samples from the upper parts of the seamount consist of very hard, glassy, thin parallel bedded ferromanganese crusts which break with a conchoidal fracture. Continuous layers of lithified carbonate, less than 1mm thick, containing an abundance of globigerina are interlayered with the ferromanganese beds at intervals of a few millimetres. The ferromanganese sediments are remarkably free from detrital material which may have been swept from the upper parts of the seamount by strong currents.

Samples from the middle slopes are well bedded, porous and friable and resemble manganese nodules in some respects. Bedding planes consist of alternating light and dark bands and the layers and slabs lack central nuclei. The clastic content ranges from 4 to 6 per cent and is composed mainly of quartz, plagioclase and orthoclase, and apatite which is present in the crusts from the upper slopes appears to be absent. Carbonate layers are not common in samples from the middle and lower slopes. The ferromanganese encrustations from both the upper and middle slopes appear to be continuous and are estimated to be at least 30 cm thick.

Ferromanganese sediments on the lower slopes of the seamount are semiconsolidated, contain 33 per cent detrital material with a large assortment of minerals, and have a correspondingly lower content of manganese and iron.

Two manganese mineral phases, γ-MnO_2 and $Mn_2O_3.H_2O$, were identified in the San Pablo crusts; most of the iron- and manganese-oxide occurs in an amorphous state. The γ-MnO_2 mineral phase is found mainly on the upper slopes where oxygen was more abundant in the sedimentary environment.

The ferromanganese sediments contain 10 to 17 % Mn, 13 to 20 % Fe, 0.15 to 0.30 % Co, 0.10 to 0.25 % Ni, 0.05 to 0.09 % Cu, 0.06 to 0.09 % Zn, and minor amounts of other constituents. The manganese content is remarkably constant in the crusts but the content of iron increases with depth and concentrations of cobalt and nickel vary with manganese content.

Bermuda Rise, DSDP Site 9
MN-35 32°46.4'N 59°11.7'W
DSDP Site 9

About 160 km west of the Sohm Abyssal Plain the seafloor at a depth of 4965 m consists of low linear parallel ridges that trend northwest with scattered seamounts that rise 300 m from the featureless plain between the ridges. Cherty sediments, derived from Eocene radiolarian oozes, occur as lenses at 671 and 759 m in the core. Sediment above these depths is dominantly olive grey to

dark grey-green with local yellow-brown bands; nearer the basement the colour changes to yellow-brown, red-brown and to very dark reddish brown. Dense manganese concretions with botryoidal and dendritic forms are present in the dark red-brown silty clays overlying the basement rocks. About 90 m of chert ooze located between olive-grey and red-brown sediments was intersected in drill holes in this area (Peterson et al., 1970).

DSDP Site 10
MN-36 32°51.73'N 52° 12.92'W

Nannofossil-foraminiferal chalk ooze and deep-sea clay and chert layers were recovered from a depth of 4612 m in 76 m of Miocene sediment above the basement rocks. The calcareous ooze varies from pale brown to grey and the clay sediments are yellow-brown, brown and dark brown. The clay zone varies in composition. Some parts consist of zeolite and clay, and more typical dark brown to pale brown nannofossil-rich layers, with the brown pigment consisting of dark red ferruginous particles. Layers are commonly 2 to 5 cm thick and are dark to light brown containing glass shards, feldspar crystals, mineral aggregate particles and altered volcanic debris (Peterson et al., 1970).

Central Bermuda Rise, DSDP Site 386
MN-37 31°11.2'N 64°14.9'W

Chloritized subalkaline basalt from a depth of 4783 m is cut by hydrothermal veins (Tucholke et al., 1979).

MINERAL OCCURRENCES IN THE SOUTH ATLANTIC

North Brazilian Ridge Rise
MN-38 00° 40°W

Sediment cores recovered from a large area along the continental slope and rise from 5°S to 5°N along 40°W longitude contain thin layers of iron-rich crust. Damuth (1977) reported that generally the upper 20 to 85 cm of each core is light-orange-tan to medium-brown foraminiferal marl or ooze. The calcium carbonate and foram content generally decreases downward and the lower few centimetres of the section consist of brown calcareous clay, often rich in manganese oxide. The base of this pelagic section is marked in most cores by a thin, 1 to 10 cm, rust-coloured semi-indurated iron-rich (5 to 22 %) crust. This crust, which marks the Pleistocene-Holocene boundary, is diachronous from core site to core site and generally ranges in age from 8000 to 15 000 years. Grey hemipelagic clay is present below the iron-rich crust and the upper parts of the sedimentary section between the Amazon River delta and the west part of the Romanche Offset appear to have been lost by erosion or slumping. The source of the iron and manganese in the sediments is uncertain.

Romanche Offset Zone, Mid-Atlantic Ridge.
MN-39 0°58.6'S 24°30.8'W

Angular blocks of metabasalt with stockworks and disseminated copper and iron sulphide minerals were dredged at depths of 2700 to 3100 m in this area near the intersection of the Romanche offset zone and the western axial segment of the Mid-Atlantic Ridge. The main sulphide mineral, chalcopyrite, is associated with pyrite and pyrrhotite and secondary alteration minerals including goethite and lepidocrocite, hydrated copper chloride, and copper-iron oxide minerals that contain up to 13 % copper. The vein material in the altered basalt consists of sulphide minerals, chlorite, nontronite, epidote, albite, calcite, and zeolites (Bonatti, et al. 1976).

Guinea Basin
MN-40 00°36.37'S 01°32.2'E

Brown metalliferous sediment composed of amorphous iron and manganese oxide was recovered at a depth of 2350 m from the summit of a seamount. Analyses of the sediment-crust show a range in Mn content from 10 to 18 %, about 24 % Fe, 0.27 to 0.50 % Co, 0.34 to 0.28 % Ni, 0.07 to 0.08 % Cu, 0.19 to 0.16 % Zn and 4 to 9 % Si (Ridout et al., 1984).

Rio Grande Rise

Cores recovered by the Deep Sea Drilling Program from boreholes listed below provide a cross section of basal sediments extending from the Mid-Atlantic Ridge westward along the Rio Grande Rise. More than 200 samples from these cores, representing iron and manganese metalliferous sediment, show that the basal sediments far from the crest of the ridge are relatively rich in Fe, Mn and P, and poor in Si, Al and Ti and that submarine volcanism has been a source of sedimentary material since Eocene or even Late Cretaceous time (Bostrom et al., 1972).

MN-41	Hole 14 water depth 4343 m.	28°19.89'S	20°56.46'W
MN-42	Hole 15 water depth 3927 m.	30°53.38'S	17°58.99'W
MN-43	Hole 16 water depth 3527 m.	30°20.15'S	15°42.79'W
MN-44	Hole 19 water depth 4677 m.	28°32.08'S	23°40.63'W
MN-45	Hole 20 water depth 4500 m.	28°31.57'S	26°50.58'W

Sediments from DSDP Site 20 range in age from Pleistocene to Upper Cretaceous and include the following lithologies: Yellow-brown nannofossil clays with local patches of manganese nodules; yellow to dark brown nannofossil ooze and clay with hematite and zeolite; interbedded dark brown zeolite clay — red clay — yellow and brown marl ooze; hematitic brown nannofossil clay and ooze; chalk ooze; brown and pink chalk ooze containing rhombs of rhodochrosite and dolomite; weathered basalt; and marble.

MN-46 Hole 22 at 30°00.31'S 35°15.00'W,
water depth 2106 m.,
intersected chert layers in a sedimentary section with similar lithology (Maxwell et al., 1970).

MINERAL OCCURRENCES IN THE SOUTH PACIFIC

Peru Basin and Bauer Deep

MN-47 09°00'S 83°31'W

MN-48 12°01'S 81°54'W

MN-49 13°01'S 101°31'W

Basal metalliferous sediments cored at these sites in the Bauer Deep and in the Peru Basin east of the Galapagos Rise contain 20 to 30 % Fe, 4 to 15 % Mn, 4 to 20 % Si, and are enriched in Cu, Ni, Co, Cr, Zn, and some of the rare earth elements (Dymond et al.,1973).

Bauer Deep

MN-50 12°35'S 95°45'W
water depth 3500 to 4500 m

The Bauer Deep, situated between the East Pacific Rise, and the Galapagos Rise contains extensive deposits of metalliferous sediment that are believed to be derived from hydrothermal sources on the seabed. The metalliferous sediments recovered from more than 10 sites in this general area contain 2 to 19.5 % iron, 1 to 6.3 % manganese, and are enriched in Cu, Ni, Co, and Cr (McMurtry and Burnett, 1975).

MN-52 08°34'S 98°18'W
water depth 4098 m
08°22'S 102°14'W
water depth 4124 m
09°02'S 97°36'W
water depth 4080 m

MN-53 07°20'S 103°02'W
water depth 4352 m
07°44'S 101°26'W
water depth 4352 m
07°51'S 100°41'W
water depth 4172 m

MN-54 05°53'S 102°40'W
water depth 4321 m.

Cores of sediment up to 7 m long at these sites are commonly free of carbonate and are composed of Fe-montmorillonite and ferromanganese compounds in the form of colloid-size particles and micronodules. Analyses of samples calculated on a carbonate free basis show 11 to 21 % Fe, 3 to 6 % Mn, 1 to 2 % Ca and Mg, 1 to 2 % combined Na and K, 2 to 3 % Al, 30 to 50 % SiO_2, 1 to 2 % Ba, and enrichment in Ni, Cu, Zn, Co, and Sr.

A large proportion of the iron occurs in the Fe-montmorillonite clay and metallic elements are believed to be adsorbed on the iron and manganese oxide colloids and on clay minerals. Cu and Zn are enriched in both the oxides and montmorillonite clay. Inverse correlations are found between SiO_2 and Fe, and Zn, Cu, Fe, and Ni correlate with Mn, but the Mn/Co relationship is uncertain. Sediment accumulation rates are about 2.5 mm/1000 a (Sayles et al., 1975; Sayles and Bischoff, 1973)

MN-55 10°22'S 103°50'W
water depth 4267 m
10°22'S 102°38'W
water depth 4267 m
10°22'S 101°02'W
water depth 4323 m
10°05'S 99°42'W
water depth 4237 m

Sayles and Bischoff (1973) and Sayles et al. (1975) report sediments rich in iron and manganese from these areas that are typical of the metalliferous sediment throughout the region between the East Pacific Rise and the Galapagos Rise. They contain little or no $CaCO_3$ but concentrations of Fe up to 18% and Mn up to 6.5% and low amounts of Al and Ti are typical. Concentrations of Cu, Ni, and Zn are high relative to more typical pelagic sediments. A non-detrital smectite makes up 70 to 90 per cent of the sediment and Fe and Mn oxides in the form of micronodules comprise 10 to 20 per cent. Detrital material makes up less than 10 per cent of the sediment samples (Sayles and Bischoff 1973; Sayles et al. 1975).

MN-56 08°22'S 102°14'W
water depth 4124 m
13°2'S 104°41'W
water depth 3780 m

MN-57 14°41'S 113°29'W
water depth 3010 m

Metalliferous sediments from these sites reported by Dymond et al. (1973) are 1 to 9 m thick and consist mainly of amorphous material, iron-rich montmorillonite, iron-manganese hydroxide, goethite and various manganese hydroxides. The iron content in these sediments ranges from 12 to 16 %, Mn about 4.6 %, Si 3.5 to 14.5%, and they are enriched in Cu, Ni, Co, La, and probably in other elements.

MN-55 09°55'S 101°09'W
water depth 3780 m
10°04'S 102°10'W
10°60'S 103°45'W

MN-51 11°33'S 97°27'W

MN-56 11°59'S 103°21'W
12°56'S 103°34'W
13°04'S 103°29'W
13°02'S 104°41'W

Heath and Dymond (1977) report that metalliferous sediments from the above locations are composed of iron-rich smectite mud and iron and manganese oxyhydroxides. These chemical and biogenic sediments contain 9 to 21 % Fe, 3.7 to 7.2 % Mn, 14 to 21 % Si, 1 to 2.3 % Ba, and are enriched in Cu, Ni, Zn, and other minor elements.

Central Basin south of Bauer Deep

MN-58 16°21'S 104°48'W
17°52'S 101°04'W
18°53'S 103°39'W

MN-59 18°43'S 100°55'W

MN-60 20°03'S 95°18'W

MN-61 23°52'S 106°09'W

Iron and manganese rich metalliferous sediments at these sites in the Central Basin area south of Bauer deep and east of the East Pacific Rise contain 9 to 12 % Fe, 2 to 4.5 % Mn, 18 to 22 % Si, and are enriched in Cu, Ni, Zn, and other minor elements (Heath and Dymond, 1977).

Juan Fernandez "microplate".

MN-62 31°S to 35°S 109°W

Hydrothermal activity was detected in this plate area located west of the East Pacific Rise and a north-trending rift zone identified at 109°W (Craig et al., 1983).

East Pacific Rise

MN-63 05°48'S 107°00'W
water depth 3157 m
06°06'S 106°43'W
water depth 3073 m

MN-64-1 09°55'S 101°09'W
water depth 4493 m

MN-64 10°32'S 110°04'W
water depth 3111 m
10°38'S 110°32'W
water depth 3145 m

Cores from these sites on the crest of the East Pacific Rise consist of metalliferous sediment composed largely of iron-rich montmorillonite clay (nontronite) that is believed to be of hydrothermal origin. Extensive beds of this kind of clay may serve as a reservoir for iron and silica released by hydrothermal alteration of basalt at ocean spreading centres (McMurtry and Yeh, 1981).

MN-65 07°50'S 108°08'W

MN-66 10°38'S 109°36'W

Dredge hauls returned samples of iron-rich sediment, manganese oxide crusts, and basalt from seamounts at these sites. The sediment consists of friable red-yellow fragments containing 30 % goethite, and amorphous silica. Analyses show up to 32 % Fe, 2.4 % Mn, 17.6 % SiO_2, 1 % Al_2O_3, and a relatively high content of Ni, Co, Cr, Cu, Ba, B, and Sr. The manganese oxide crust contains up to 40 % Mn, 17 % Fe, and an unusually high content of Ni (0.45 %) and Co (0.68 %) (Bonatti and Joensuu, 1966).

MN-67 08°57.42'S 109°08.37'W
water depth 3547 m
09°09.14'S 108°13.80'W
water depth 3285 m

Metalliferous sediments from active hydrothermal sites in these areas contain 13 to 14 % Fe, 3 to 4 % Mn, and are enriched in Cu, Zn and other minor elements close to hydrothermal vents (Cronan and Varnavas, 1981).

MN-68 15°S 115°W

A helium-rich plume in the ocean has been reported at a depth of 2500 m which can be traced 2000 km westward from the Rise area. It is believed to mark the existence of a very large hydrothermal field in this part of the East Pacific Rise (Lupton and Craig, 1981).

MN-69 16°56'S 121°12'W
water depth 3540 m.

MN-70 16°57'S 116°18'W
water depth 3407 m

MN-71 17°02'S 113°54'W
water depth 2830 m

One core from the crest and two from the flank of the East Pacific Rise are composed of iron and manganese bearing metalliferous sediment, minor metallic elements, rare-earth elements, uranium and thorium (Bender et al., 1971).

MN-72 17°07'S 113°51.47'W

Metalliferous sediment intersected in a core from this site near the East Pacific Rise contains 15.6% Fe, 5.3% Mn, and 0.07% Cu (Marchig and Gundlach, 1982).

MN-73,-74 17.9°S to 18.6°S,
21.1°S to 21.7°S, 113°25'W
water depth 3324 to 2650 m

Grabens up to 90 m in depth in these areas occur on the crest of the East Pacific Rise and are sites of recent faulting and intensive hydrothermal activity. Deposits of iron, copper, and zinc sulphide occur in the graben basins and metalliferous sediments composed of iron and manganese oxide are deposited mainly on the western flank of the ridge outside of the grabens.

Sediments were sampled on a 75 km traverse from east to west across the crest of the East Pacific Rise at 18.5°S. Oxyhydroxide bearing calcareous oozes dominate the eastern flank and iron-manganese marls characterize the sediments on the western flank of the Rise. Eastern flank sediments show high $CaCO_3$ and low Fe, Mn, Cu, and Zn concentrations. A lobe of sediment enriched in Fe and Mn extends to the west of the rise crest at 19°S and hydrothermal accumulation rates are 2 to 10 times greater on the west flank and crest areas than on the east flank. The Fe/Mn ratios at crest locations on the traverse range from 3.4 to 4.2 and at flank positions from 2.9 to 3.3 and may reflect fractional dispersion of these elements away from their hydrothermal source. Higher Si/Al ratios of 18 to 30 in the crest and western flank sediments may reflect relatively widespread westward dispersion of silica.

Iron, copper and zinc sulphides were recovered from five stations in the northern axial trough and from one in the south. Four of the northern stations provided only

basalt samples which contained pyrite, cubanite, chalcopyrite and zinc sulphide. A fragment of a chimney structure rich in iron, zinc and copper sulphide was recovered from another site in the north graben. Sulphide samples recovered from the southern graben at 21.5°S are variable in composition and show chimney and relict biogenic structures. (MN-74) Metal content varies from 0.2 to 35% zinc, 0.2 to 20% copper and is about 0.05% lead. A composite sample from the southern graben composed of pyrite, marcasite, chalcopyrite, cubanite, covellite, sphalerite and wurtzite contains 35.8% Fe, 9.1% Zn, 6.8% Cu, 45.5% S, and 1.2% SiO_2. Other samples from this area have sulphide minerals in stockworks and brecciated basalts (Backer et al., 1985).

MN-75 21°20'S 114°10'W
21°40'S 114°20'W

Manganese content in the sea water indicates the presence of a very large hydrothermal field in this area which may be the source of metals that were deposited in chemical sediments in the area west of this field (Boulegue and Hamelin, 1983).

West Flank, East Pacific Rise

MN-76 17°07.04'S 113°51.47'W
water depth 3211 m
19°47.97'S 114°21.10'W
water depth 3266 m

MN-76 21°00.06'S 114°42.71'W
water depth 3352 m
20°32.87'S 114°21.80'W 3327 m
20°54.84'S 114°54.84'W 3246 m

Cores of metalliferous sediment were recovered from these sites on the west flank of the East Pacific Rise near an area of intense effusive hydrothermal activity. The west side of the ridge is spreading at the rate of 7 cm/a and the east side at 9.2 cm/a, giving total annual separation of 16 cm/a. Metalliferous sediment is accumulating at a high rate and consists of about 20 % Fe_2O_3 as moderately crystalline goethite, 4 to 7 % MnO_2, in part as todorokite, 3 to 5 % SiO_2, and 2.2 % P_2O_5 as apatite. The 2 to 3 m cores representing Late Pleistocene and younger sediment are enriched in Mn, Mo, La, Cu, V, Ni, Fe, Zn, Co, and Y, in comparison to the content found in tholeiitic basalts, but concentrations of Zr, Al, and Ti are lower. Na, K, and Rb appear to be enriched in the sediment by adsorption from the seawater, and Ca, Sr, Pb, and perhaps Sc are bound to the planktonic carbonate part of the sediment (Marchig and Gundlach, 1982).

East Pacific Rise

MN-77 24°36'S 115°27'W

Core of iron-rich metalliferous sediment from this site near the crest of the East Pacific Rise contains about 26 % Fe, 9 % Mn, and relatively high amounts of minor metallic elements (Heath and Dymond, 1977).

MN-78 29°28.08'S 131°36.81'W

Hydrothermal sediments composed of greenish granular-nontronite and fragments of manganese oxide, todorokite and birnessite were found in 3.5 m of core from below a water depth of 4250 m. The nontronite contains very little Al and the hydrothermal sediment has a very low content of trace metals and rare earth elements (Stoffers et al., 1985).

MN-79 19°30'S 130°W

Hydrothermal sediment was found in four areas between the East Pacific Rise and 130°W at this latitude. The sediment ranges in age from 2 to 26 Ma from east to west and west of the Rise consists of brown calcareous ooze and siliceous biogenic debris. The youngest sediment from a site 150 km west of the rise consists almost entirely of hydrothermal material and the accumulation rate is 200-1800 mg/cm^2/1000 a, the highest in all sites (Leinen, 1982).

Central East Pacific Basin, DSDP Sites
MN-80,-81 12°30'S to 14°47'S, 90°30'W to 139°35'W

MN-82 14°01'S 122°28'W
water depth 3790 m

MN-83 14°02'S 128°29'W
water depth 3985 m

Twenty samples of cores from the two sites listed in this rectangle consist of iron-oxide rich sediments formed by exhalative sedimentary processess that are interbedded with iron-free calcareous nannoplankton oozes. Analyses of metalliferous sediment reported on a carbonate and opaline silica free basis indicate: 6 to 35 % Fe, 0.68 to 10.5 % Mn, 1 to 3.6 % P_2O_5, and anomalous enrichment in other elements including V, U, As, Hg, but low content of Al, Th, Zr, and Sc (Boström and Rydell, 1979).

MN-84 12°31'S 134°16'W .
water depth 4181 m

MN-85 06°14.20'S 136°05.8'W
water depth 4431 m

A sequence of amorphous iron oxide-rich sediments interbedded with iron-free calcareous nannoplankton oozes and siliceous radiolarian ooze occurs in the basal zone overlying basalt at these sites. These sediments have affinities with iron- and manganese-rich sediments from the East Pacific Rise. A basal iron and manganese rich facies is believed to be present over much of the central east Pacific Basin. The metalliferous sediments were probably formed by precipitation from waters enriched in metals derived from submarine hydrothermal exhalations associated with volcanism (von der Borch et al.,1971).

MN-86 0°28.9'N 133°3.7'W

MN-87 0°57'S 121°3.2'W

Basal metalliferous sediments consisting of smectite muds at these sites contain up to 16 % Fe, 5.7 % Mn, and 0.58 % P (Bloch, 1978,1981).

Tiki Basin
MN-88 15°S 135°W 4000 to 4500 m

Manganese nodules are associated with calcareous metalliferous sediment throughout much of the Tiki Basin situated between the Marquesas Fracture Zone to the northwest, the Tuamotu Fracture Zone to the northeast and the Tuamotu Archipelago to the south. Dredge samples show that sediment from the shallow zones, less than 4100 m, consists of foraminiferal calcareous oozes, and red pelagic clay is present in the deeper zones. The clay fraction of the sediments in the Tiki Basin consists mainly of iron-rich smectite. Phillipsite clay is more prevalent in the deeper zones in sediment with low content of $CaCO_3$. The content of iron hydroxide minerals increases in the deeper sediments and decreases in the $CaCO_3$ bearing upper sediments. Micronodules of manganese and iron oxide occur in the deeper sediments where there is less carbonate present.

Metalliferous sediment containing more than 10 % iron and 3 % manganese similar to that found in the Bauer Deep is widely distributed throughout the Tiki Basin. The content of iron and manganese in the metalliferous sediment increases with depth. Analyses show a range in content of Fe_2O_3 from 1.5 to 23.5 %, Mn_3O_4 from 1 to 6 %, SiO_2 from 3 to 30 %, CaO from 3 to 48 %, $Na_2O + K_2O$ from 1 to 9 %, Al_2O_3 from 0.4 to 10.5 %, TiO_2 up to 1.15 %, and a relatively high content of Cu, Zn, Pb, Ni,Co,Cr, V, Ba, Sr, and Sn (Hoffert et al., 1979).

MN-89 12°46'S 143°33'W
water depth 4380 m.

Goldberg and Arrhenius (1958) report dark brown clay sediments with manganese nodules at this site.

Marquesas Islands
MN-90 11°28.6'S 144°00.5'W
water depth 4725 m

The core site is north of the Marquesas Fracture Zone and west of the Marquesas Islands, below the carbonate compensation depth, in proximity to volcanic seamounts, on the path of important currents that are moving eastward, and where there is a lack of continental sediment. Metalliferous oxide sediment occurs at the sediment-water interface above 380 cm of cored sediment that is composed mainly of homogeneous, fine, dark brown mud, taken from a 60 m thick section. Palagonite is the main component in the upper part of the core and phillipsite clay is replaced by brown aggregates consisting mostly of smectite associated with iron oxide in the lower part. Fe-Mn micronodules are present with the coarse fraction throughout the core. The chemical composition of the clay fraction is relatively homogeneous with Si/Al ratios of 4.2, the content of Fe_2O_3 ranges from 17.8% near surface to 21.5% in the bottom sample, and the average content of manganese in the nontronite clay is 6.4 % (Clauer et al., 1982).

Tuamotu Archipelago
MN-91 20°22'S 148°02.6' W

A sediment core about one metre long collected at the foot of an abyssal hill southeast of Tuamotu Archipelago is characterized by dark reddish-brown clay with thin (1 to 4 cm) layers of ash near the top. The core is composed of smectite that has been shown by detailed mineralogical study to be iron-rich montmorillonite or nontronite clay that is similar to other iron-rich montmorillonite from the northeast Pacific. Analyses show that the iron-rich montmorillonite contains 50.17 % SiO_2, 0.77 % TiO_2, 7.11 % Al_2O_3, 11.46 % Fe_2O_3, 0.25 % FeO, 0.09 % MnO, 5.41 % MgO, 0.30 % CaO, 2.86 % Na_2O, 0.57 % K_2O, 8.02 % H_2O+, 12.03 % H_2O. Aluminous montmorillonite contains 14.39 % Al_2O_3, 1.18 % TiO_2, and less iron than the iron-rich varieties (Aoki et al., 1979).

MN-92 16°36'S 162°43'W
water depth 5125 m
16°58.5'S 161°35'W
water depth 5140 m
16°44'S 161°22'W
water depth 4685 m
16°53'S 159°08'W
water depth 5040 m

MN-93 17°28'S 160°59'W
water depth 4710 m
17°29'S 158°40'W
water depth 4890 m

Goldberg and Arrhenius (1958) report dark brown clay with manganese nodules and micronodules, phillipsite and fish debris at these sites.

Western Samoan Offshore, Southwest Pacific
MN-94,95 11°S to 16°S 170°W to 175°W

Within this area calcareous oozes are predominant in the northwest and siliceous ooze in the northeast. Manganese nodules are not abundant but occurrences of brown mud are widespread. Manganese and iron oxide crusts coating pebbles of volcanic rock were found around the following locations: 14°57'S 172°12'W; 13°22'S 173°W; 11°53'S 172°55'W; 15°31'S 173°10'W (Exon, 1982).

Lau Basin
MN-96 15°23'S 174°41'W

The Lau and North Fiji basins are situated near the subduction zone where the Pacific Plate plunges beneath the Indo-Australian Plate. The Lau Basin extends along the west side of the Tonga Trough and Ridge and trends northeast. Fragments of an extinct chimney were dredged from a depth of 2100 m from the axial region of a spreading ridge in a rift valley with walls 200 to 300 m high. These fragments consist of concentric layers of sphalerite, pyrite and chalcopyrite and an abundance of amorphous silica in spherical to irregular masses up to 5 mm in size with barite impregnated in the sulphide minerals. Fresh

glass rinds on pillow lavas have a basaltic andesite to andesitic composition and dacite vitrophyres were dredged from a nearby site at 15°24'S and 174°40'W. The central part of the Lau Basin is characterized by tholeiitic basalt and Valu Fa Ridge and the hydrothermal vent site may be located on propagating rift zones where the volcanic rocks are more fractionated than the typical Lau Basin magmas (Craig et al., 1986; Hawkins and Helu, 1986; Volpe et al., 1986).

Northern Lau Basin
MN-97 18°40'S 176°15'W

The morphology of the area is dominated by northeast striking ridges and depressions and a ridge marking the active spreading area was traced for 47 km by the opaque character of the seismic reflections and a central magnetic anomaly. The older ridges show evidence of submarine weathering and initial encrustations of manganese oxide and yellow patches on the active spreading ridge are believed to be hydrothermal precipitates (von Stackelberg et al., 1985).

Southern Lau Basin and Valu Fa Ridge
MN-98 22°15'S 177°30'W

The southern Lau Basin is located between the morphological axis of the Lau Basin which trends northeast and the volcanically active Tonga Island Arc and includes a potential spreading centre in the western part and a spreading axis in the eastern part. The Valu Fa Ridge centred at 22°15'S and 176°37'W extends northeast for 60 km and rises to a minimum depth of 1600 m. Several seamounts and sediment-filled basins are situated east and west of this ridge. Bedded lava flows and frothy aa lavas indicate that this ridge was formed recently. It is composed of iron-rich andesites that have a high content of SiO_2, Fe and Ti and a low content of Mg. Yellow zones appear to mark hydrothermal sediment patches. Pale yellow porous nontronite recovered from this area has a low content of trace elements and is considered to be of hydrothermal origin. Manganese oxide (birnessite) crusts with a high Mn/Fe ratio are similar to those described in the Tonga-Kermadec Ridge to the east by Cronan et al.(1982).

Four dredge samples from the summit of Valu Fa Ridge consisted of sulphide impregnated volcanic rocks. Hydrothermal oxide and sulphide minerals were observed on seamounts up to 70 km from Valu Fa Ridge. Samples contained pyrite, chalcopyrite and opal and the volcanic rocks impregnated with sulphide are lighter in colour and contain up to 63% SiO_2, 15% Al_2O_3 and less than 1.5% MgO (von Stackelberg et al., 1985).

Lau Basin Traverse

Accumulation rates of metalliferous hydrothermal sediments from five sites on a traverse across the Lau Basin were studied by Cronan et al. (1986). Traverses were made across two areas of zero-age crust and cores of sediment from the one traverse which is believed to cross an active spreading centre were located at:

MN-97 18°31.9'S 178°58.2'W
water depth 2604 m
18°31'S 177°43.3'W
water depth 2594 m
18°36.5'S 177°08'W
water depth 2444 m
18°37.2'S 176°42.9'W
water depth 2469 m
18°34.1'S 176°19.7'W
water depth 2724 m

The highest accumulation rates were found in samples from the last site listed, U64, that is supposed to be close to a spreading ridge and the accumulation rates in $\mu g/cm^2/1000a$ for Mn range from 7101 to 18 112; Fe from 26 479 to 251 230; Zn from 55 to 251 230; Cu from 108 to 743; and As from 19 to 80. The nondetrital accumulation rates of Mn, Fe, Cu, and Zn in core U64 are much higher than bulk accumulation rates in normal pelagic sediments and are similar to the accumulation rates reported in East Pacific Rise sediments and suggest a substantial hydrothermal input of metals. The nondetrital accumulation rates in cores west of U64 are lower but still above typical pelagic clay values and show a general decrease westward.

Tonga-Kermadec Ridge
MN-99 26°56'S 177°37'W
water depth 1500 to 2000 m

Manganese oxide crusts were dredged from two stations in this area. Surface material is black, granular and forms discontinuous layers a few millimetres thick on massive layered material that is hard, smooth and has a distinctive purplish-black metallic sheen. Basal material below this layered manganese oxide is granular to sugary in texture and up to a centimetre thick. Birnessite is the main mineral present. Samples contain up to 49 % manganese and are characterized by extreme fractionation of manganese from iron, and are comparatively rich in Li, Zn, Mo, and Cd (Moorby, et al., 1984; Cronan et al., 1982).

Southern Part of North Fiji Basin
MN-100 16°10'S 177°25'E
Braemar Ridge and Yasawa Trough

The southern part of North Fiji basin has very irregular submarine relief and morphological structures such as Braemar Ridge in the north and Yasawa Trough in the south. These features trend northeast to north-south in the middle part of the area where a narrow trough-like valley contains fresh basaltic lava. The basalt at one place in this valley is impregnated with hydrothermal sulphides. Braemar Ridge and vicinity are characterized by a heterogeneous suite of older rocks including serpentinized dunites, greenish dacite tuffs, volcaniclastic rocks, hydrothermal manganese crusts, and pelagic carbonate rocks (von Stackelberg et al., 1985).

Northern Part of North Fiji Basin
MN-101 14°30'S 177°E

The northern part of the basin is older and has higher sedimentation rates and the relief is much more uniform. Northwest trending ridges may represent fossil spreading centres and hydrothermal manganese crusts are present in some parts of them. Hydrothermal sulphide minerals impregnate fresh volcanic rocks and manganese oxides and iron silicates of hydrothermal origin are common at active and fossil spreading zones and on seamounts in both the Lau and North Fiji Basins (von Stackelberg et al., 1985).

Epi Island, New Hebrides Arc
MN-102 16°40.6'S 168°23.1'E
water depth 315 m
16°42.1'S 168°23.0'E
water depth 265 m
16°39.4'S 168°20.7'E
water depth 400 m
16°44.3'S 168°20.1'E
water depth 270 m
16°40.8'S 168°21.5'E
water depth 165 m

Five cores recovered near two active volcanoes off the Island of Epi in the eastern part of the New Hebrides Arc contain brick red silty beds interbedded with volcanic silty sands and volcanic glass. The red beds are predominantly amorphous iron oxide containing up to 27.5 % iron that has been precipitated from hydrothermal solutions associated with the volcanoes. Polymetallic sulphide may occur near the vents on the seabed or in the bedrock (Exon and Cronan, 1983).

Shelf off New South Wales, Australia
MN-103 28°S to 32°S 153°E to 154°E

Iron-rich sediment on the outer continental shelf of northern New South Wales, Australia, is enriched in iron and marginally enriched in P, As, and Mn when compared to other sediments of the area. The authigenic mineral phase is berthierine (chamosite) rather than glauconite which may have broken down to poorly crystalline phases of berthierine and goethite. During this breakdown of the early mineral phases foraminiferal infillings and pellets have become enriched in iron, and P and As have been incorporated in minerals by atomic adsorption. The source of phosphate in the phosphate nodules and sediments is believed to be the surrounding iron-rich sediments and the phosphate nodules are relatively enriched in Fe and As and low in P compared with phosphate deposited in areas with upwelling currents. It is believed that significant amounts of inorganic phosphate released during the reduction of the iron-rich sediments have been precipitated as carbonate-fluorapatite. This may explain the formation of phosphorites in situations where there are no upwelling currents as a source of phosphate.

Authigenic phases of outer shelf sediments off New South Wales contain from 18.9 to 33.9 % SiO_2, 5.9 to 8.5 % Al_2O_3, 27.8 to 40.9 % FeO, and 0.11 to 1.59 % P_2O_5, and significantly high amounts of Mn, As, and Zn along with other trace elements (Marshall, 1983).

Manus Back-Arc Basin
MN-104 03°09.7'S 150°16.8'E
water depth 2500 m

The Manus Basin is in a back-arc position with respect to the New Britain arc-trench system east of New Guinea and is marginal to the southwest part of the Pacific plate where spreading is taking place at a rate of more than 10 cm/a. A collapsed chimney and evidence of hydrothermal mineralization was observed over a horizontal distance of 150 m near the crest of a small axial volcano inside the rift valley of the spreading centre. Dredge samples from within 100 m of this site contained fresh basalt but no sulphide material. Several inactive chimneys and patches of yellow sediment, probably nontronite clay, were photographed along with live fauna and faunal remains. The chimneys appear similar to others found on the East Pacific Rise that consist of sulphide, sulphate and silicates and are associated with mounds formed by the mass wasting of the chimneys (Both et al., 1986).

DSDP SITE 323
MN-105 63°41'S 97°59'W
water depth 4993 m

Clay smectite sediments 30 to 74 m above the basement are enriched in Mn, Fe, Cu, Ni, Co, Mo, and Sr (Anderson et al., 1976).

MINERAL OCCURRENCES IN THE NORTH PACIFIC

Philippine Trench
MN-106 12°48.43'N 127°49.8'E

Basal metalliferous sediment was recovered in cores from this area on the outer arch of the Philippine Trench. The samples consisted of dark brown ferruginous zeolite clay with nannofossil and radiolarian-rich beds that are probably late Eocene in age (Bonatti et al., 1979).

West Philippine Basin

MN-106	13°N	DSDPS Leg 31	Site 291
MN-107	22°34.74'N	131°23.13'E	Site 294
	2°33.76'N	131°22.04'E	Site 295

Metalliferous sediment was recovered from bore holes put down in the Deep Sea Drilling Program at these sites located 500 km southwest and 580 km northeast of the Philippine Ridge. In both areas the metalliferous sediment consists of brown layers of ferruginous clay up to 158 m thick of Eocene age that rests directly on the basaltic basement. The sedimentation rate of the brown clay is estimated to be 2-3 mm/Ma and water depths are 5700 to 5812 metres. The brown clay contains up to 62 % SiO_2, 44 % Fe, 9.2 % Mn, and anomalously high amounts of Cu, Ni, Co, Zn, rare earth elements, and other constituents (Bonatti et al., 1979; Ingle et al., 1975).

Mariana Trough and Back-Arc Basin
MN-108 18°N 144°45'E

Cores from areas of high heat flow in the rift valley of the Marianas spreading centre contain fine-grained grey-green muds dominated by detritus possibly from the Marianas Arc to the east. Cores from mounds in the Marianas Trough contained brown oxidized pelagic clay composed of 95 % detritus and small amounts of amorphous hydrothermal material. The mounds average 20 m in diameter, and are located along small scarps. The lower part of one mound consisted of ferruginous hydrothermal sediment with veins of brownish-yellow smectite. The upper part of the mound was dark brown sediment mixed with friable brownish-black crust rich in manganese (Leinen and Anderson, 1981).

An abyssal hill site with local high heat flow on the 3 Ma old west flank of the Marianas Trough has sets of oblique fault scarps and clusters of domes, 50 to 1000 m in diameter. Rocky knobs on the domes that are 20 to 30 m high are encrusted with manganese oxide. The southern dome in the western back-arc basin area is about one kilometre in diameter with a 300 m wide summit area at 3475 m below sea level. It has several small satellite domes on its western side. Most of the south and east side of this 100-m-high dome has a 100 to 150 m wide band of rough massive outcrops of manganese encrusted pumice.

Bottom sediment in depressions of the back-arc basin area is up to 5 m thick and consists of unconsolidated siliceous clay rich in diatoms and radiolarian tests. It tends to flow or pond and is absent from slopes steeper than 15° (Lonsdale and Hawkins, 1985).

Mariana Trough
MN-108 18°13.3'N 144°42.2'E

Hot patches on the seafloor emitting more than two watts of geothermal energy per metre or about 50 times normal, reported by Anderson (1982), are strong indications of hydrothermal activity in this area. The largest methane anomaly ever found in the oceans was recorded over the back-arc basin spreading centre and a 26 per cent increase in primordial ^3He was discovered at this site. These anomalies were early indications of active hot vents at the crest of the Mariana back-arc basin (Anderson, 1982).

MN-109 02°24'N 166°7'W
water 5293 m

Metalliferous sediment from this drill site contains 20 to 28.5% Fe, 4.5 to 6.9% Mn, 7 to 8% Si, and is enriched in Cu and Ni (Dymond et al., 1973). A core from the area contains a 163 m section of radiolarian ooze with thin beds of chert in the lower 16 m and dark brown layers that contain iron-manganese micronodules (Winterer et al., 1971).

Line Islands Ridge and Mid-Pacific Mountains location
MN-110 09°09'N 164°48'W
water depth 2100 m

MN-111 13°08'N 165°02'W
water depth 3350 m
13°05'N 165°29'W
water depth 4380 m

MN-112 19°22'N 171°04'W
water depth 1880 m
19°22'N 170°99'W
water depth 1190 m

Manganese-iron crusts rich in cobalt occur on the flanks and plateau areas of seamounts at the above locations and water depths. The Line Islands Ridge and Mid-Pacific Mountains seamount areas are related to late Cretaceous basaltic volcanism. Cobalt concentration in the plateau crusts and nodules increases from 0.4 % at water depths greater than 4000 m to more than 1 % in seamount slopes and summit areas less than 2000 m deep. The top 0.5 cm of crusts from water depths between 1500 and 1100 m show maximum contents in cobalt up to 2 %, Mn and Ni correlate positively with Co but Cu shows an inverse relationship with these metals. Manganese oxide minerals are intimately mixed with amorphous iron hydroxide and are deposited on altered basalt and hyaloclastic rocks of late Cretaceous age. Dried samples of the metalliferous crusts contain 13 to 16 % Fe, 18 to 29 % Mn, 0.6 to 1.38 % Co, 0.2 to 0.6 % Ni, 0.03 to 0.15 % Cu, 3.3 to 7.8% SiO_2, 0.4 to 1.4 % Al_2O_3, 2 to 4.5 % Ca, 0.3 to 0.8 % P_2O_5, 1 to 1.7 % Ti, and Mn/Fe ratios from 1.3 to 2.1 (Halbach,1982).

Loihi Seamount, Hawaii
MN-113 18°52'N 155°15'W

An extensive hydrothermal field associated with recent lava flows was mapped along the inner walls of the southern rim of the crater of Loihi volcano. Samples dredged from the hydrothermal field consist of yellow-brown crystalline goethite and iron-rich nontronite clay mud and contain 22.8 to 33.8 % Fe, 1 to 2 % Al and are enriched in Mn, Cu, Ni, Pb, Cd, As, and Hg (Malahoff et al., 1982).

West Galapagos Fracture Zone
MN-114 00°40'N 123°33'W
MN-115 06°44'N 129°30
MN-116 09°17'N 124°09'W
MN-117 05°N 101°W
Metalliferous sediments are reported at these areas (Boström,1980).

DOMES Site C, (Deep Ocean Manganese Environmental Study)
MN-118 15°07'N to 15°17'N 125°58'W to 126°04'W

Metalliferous sediment sampled at several sites in this area is dark brown in colour and composed of magnesian-rich nontronite clay mixed with pelagic clay. Lower parts of the cores consist of about 40 % metalliferous sediment mixed with pelagic clay and contain 40 to 50 % SiO_2, 10 to 15 % Al_2O_3, 8 to 12 % Fe_2O_3, 1 to 2 % Mn, 3 to 4

% MgO, 3 to 8 % Na_2O and K_2O, and have significantly higher content of Ba, Cu, Ni, Sr, Zn, V, and other minor elements. The calculated composition of the metalliferous sediment fraction shows an average content of 59 % SiO_2, 28.9 % FeO, 7.3 % MgO, 4.6 % Mn, and enrichment of Mo, Cu, V, Pb, Sr, and Y (Bischoff et al.,1979; Bischoff and Rosenbauer, 1977).

MN-119 01°26.5'N 113°48.5'W
water depth 3854 m

Basal metalliferous sediments composed of yellow and brown chalk and mudstone contain up to 10 % iron and manganese oxide (Bloch, 1981).

Axial Zone, Galapagos Rift System

MN-120 00°40'N 86°15'W
00°50'N 85°50'W

The Galapagos Ridge extends eastward from its intersection with the East Pacific Rise at 2° N and 102° W and is divided into a number of spreading segments that are offset by north trending transform faults. It separates the Nazca Plate to the south from the Cocos Plate to the north. A narrow rift valley at its crest is 3 to 3.5 km wide with an average depth of 2.5 km below sea level. Spreading rates have averaged about 7 cm/a over the last 3 Ma. A segment of the rift zone about 30 km long at 86° W has been mapped in detail (Ballard et al., 1982). Sheet flows dominate in the valley floor in the western part of this segment and pillow lavas in the eastern part. Hydrothermal vent fields are active along the axial zone of this segment where extensive deposits of sulphide minerals and large accumulations of yellow-brown ochre were observed.

Malahoff (1982) reported an overlapping spreading centre on the Galapagos Rift in the vicinity of 85°50'W and 0°45'N where water depths are about 2850 m. In this area the axial valley of the Galapagos Rift forms two rift valleys with axes about two kilometres apart. The northern valley is about 1200 m wide and is marked by a prominent median ridge 30 m high that is crested by volcanic edifices 15 to 40 m high. The southern rift valley, about 2000 m to the south, is marked by an axial rift 20 to 50 m deep that is partly filled with pillow lava. The flanks of the rift zone consist of pillow lava with a light covering of sediment. The two rift valleys are separated by a fault block 500 m wide and about 50 m high. Iron and manganese oxides and copper-iron sulphide minerals have been deposited by effusive hydrothermal processes along the rift valley walls but none were observed along the axes of the rifts.

Three sites along the bounding faults of the horst that separates the rift valleys have inactive chimneys that are composed of polymetallic sulphide minerals. The largest deposit, located along the northern wall of the southern valley consists of a mass of coalesced chimneys and stacks about 35 m high and 20 to 200 m wide that extends along the fault zone for 1000 m. Seven samples from different parts of this mineral deposit have an average content of 40 % S, 38 % Fe, 6.5 % Cu, 7 % SiO_2, 1 % Zn, 0.5 % Mn, 0.3 % Al_2O_3, 360 ppm Se, 250 ppm Co, 270 ppm Mg, 181 ppm Mo, 215 ppm Pb, 45 ppm As and Ba, and less than 40 ppm of Cd, Cr, P, Hg, Ni, Sn, V, U and W. Gold content is less than 0.2 ppm, silver averages 21 ppm, and palladium is less than 0.05 ppm. The samples were composed mainly of pyrite, chalcopyrite, sphalerite and amorphous silica. The main sulphide deposits appear to be flanked to the east and west by iron oxides that were deposited around vents 10 to 20 cm high that are now inactive.

Sulphide mounds formed by hydrothermal activity along the southern wall of the northern rift valley are composed of inactive chimneys 2 to 5 m high and 1 to 2 m in diameter. The mounds formed by coalesced chimneys are distributed along a fault scarp over a distance of 100 m to 750 m. Basalt talus along the scarp is cemented by a blanket of sulphide precipitate about 1 m thick. The sulphide consists of pyrite, marcasite, chalcopyrite, sphalerite and covellite, and is associated with amorphous silica and some hydrated copper sulphate. Samples of sulphide contain up to 27 % Cu, 31 % Fe and 1.5 % Zn.

Oxide materials from this area consist of manganese oxide, birnessite containing 42.5 % Mn, 2.3 % Zn and 0.12 % Cu, and amorphous iron oxide containing 33.8 % Fe and 0.48 % Zn. Samples collected 2 km west of this area on small domes and hummocks along the spreading axis are coated with orange iron oxide and composed mainly of amorphous iron oxide that is veined by birnessite and other manganese oxide. (Ballard, 1982; Malahoff et al., 1983; Malahoff, 1982; Corliss et al., 1979; Edmond et al., 1979).

MN-120 00°57'N 85°29'W
water depth 2500 m

Sediment dredged at this site, about 28 km north of the axis of the Galapagos Rift, consists of alternate layers of manganese crust and green nontronite clay. It was probably deposited near the 85°W fracture zone between the Galapagos and Ecuador Rifts (Malahoff et al., 1983).

Manganese Mounds Field South of Galapagos Rift Zone

MN-121 00°30'N 86°W
00°38'N 86°15'W
water depth 2700m

An area of 200 km^2 centred along the 86°W longitude line that extends from 17 to 30 km south of the spreading axis of the Galapagos Rift has thousands of manganese-rich mounds that are distributed for 27 km along major fracture and fault zones that strike east-west parallel to the Galapagos Rift. The mounds of lithified sediment are 5 to 20 m high, 20 to 50 m wide, and are arranged in linear chains 1 to 2 km long parallel to faults or cross fractures. The mounds have formed along fractures and faults where low temperature hydrothermal fluids seep through the sediment cover.

Cores through these mounds show a lithological sequence from top to bottom that consists of Mn-oxide

cappings (6 to 270 cm thick), Fe-rich green nontronite clays intercalated with pelagic sediment, and basement basalt. The Mn-oxide crusts consist of todorokite, birnessite, and amorphous compounds that contain 58.5 % MnO, 0.31 % Fe_2O_3, 0.81 % SiO_2, 4 to 6 % of CaO and MgO, 3.90 % Na_2O, 26 % Loss on ignition, and significant content of trace elements. The green clay contains 0.10 % MnO, 27.5 % Fe_2O_3, 52.2 % SiO_2, more than 5 % combined Na_2O and K_2O, 4.4 % MgO, and low but significant content of trace elements. The underlying ferrobasalts are altered along fractures where minor amounts of calcite and pyrite are present in vesicles and in association with smectite and Fe-oxides along joints (Lonsdale, 1977; Schrader et al., 1980; Williams et al., 1979; Lalou et al., 1984).

MN-121 00°35'N 86°07'W

Cores and dredge samples from this area of mounds and metalliferous sediments are composed of brown, olive-brown, greenish black, and dark yellow to green siliceous nontronite muds and fragments and concretions of Fe-Mn oxide. They contain about 20 % Fe, 10 % Mn, 40 to 50 % SiO_2, but appear to be depleted in many minor metals (Varnavas and Cronan, 1981; Corliss et al., 1978).

MN-122 02°43'N 95°15'W

Manganese oxide crusts 2 to 6 cm thick dredged in this area contain 25 to 65 % Mn, a very low content of Fe, and enrichment in Cu, Zn, Ni, and Co (Moore and Vogt, 1976).

MANOP Site
MN-123 08°45'N 104°00W

Basal rocks at this site 25 km east of the East Pacific Rise are 500 000 years old and are covered by 550 cm of sediment. The lower 150 cm of sediment are reported to be of hydrothermal origin and rich in manganese and iron with Fe/Mn ratios from 2.6 to 2.9 (Heath and Lyle, 1982).

Seamounts East Pacific Rise
MN-124 08°46'N.

Two seamounts are symmetrically located about 35 km to the east and west of the axis of the East Pacific Rise at this latitude. They are believed to be remnants of a seamount that was split by spreading along the rise axis. Earthy brown hydrothermal sediment was dredged from one of the seamounts (Hekinian and Fouquet, 1985).

East Pacific Rise
MN-125-1 11°30'N 103°55'W

Hydrothermal venting was encountered in a graben 20 m deep near this site (Gente et al., 1986).

Feather Duster Site, East Pacific Rise
MN-125 10°56'N 103°41'W

A vent field 65 m by 45 m in area is situated on a 20 m high fault scarp that trends 340° to 350° along the eastern side of the main rift valley. Biological communities are localized around hydrothermal fissure vents in the north-central part of the field and around a 300-tonne mound of polymetallic sulphide located on a 3-m-high fault scarp that is 15 to 20 m east of the rift valley wall. The mound is composed of broken chimneys and spires that show concentric zoning from $CuFeS_2$ cores to ZnS-rich zones to FeS_2 and iron oxide rich rims. Active "black smoker" vents bearing anhydrite are present on the mounds. The bulk samples contain from 3.95 to 41.6 % Zn, and 0.30 to 5.3 % Cu (McConachy et al., 1986).

Clipperton Seamount
MN-126 10°30'N 109°W
water depth 2890 to 3250 m

This volcanic edifice, located about 18 km west of the axis of the East Pacific Rise, rises 1000 m above the seafloor. Local volcanic peaks, about 200 m high, are capped with ocherous Fe-Mn material of hydrothermal origin. Fragments of basalt, manganese oxide and sulphide were dredged in this area. The crusts are 3 to 4 cm thick and contain 6 to 11 % Fe and 3 to 7 % Mn (Hekinian and Fouquet, 1985).

Segment of the East Pacific Rise
MN-127 12°38'N to 12°54'N 103°54'W to 103o58'W

This segment of the East Pacific Rise, mapped and studied in detail by Choukroune, Francheteau and Hekinian (1985), has a continuous active tectonic and volcanic zone about 5 km wide. Volcanism and hydrothermal activity are restricted to a central graben, about 0.5 km wide. The average depth of the graben floor is about 2630 m. More than 80 active and inactive hydrothermal vents were recognized that form local and discontinuous mineral deposits averaging 50 m in diameter. The mineral deposits are scattered over a width of 200 m along the axial zone of the ridge in a 20 km long segment of the axial graben north of 12°47'N. Camera stations and observations from submersibles indicate that the average spacing between hydrothermal deposits along the ridge axis is between 100 and 200 m. Hydrothermal activity in the axial zone of the ridge south of this segment appears to be waning. Each field consists of irregular and conical-shaped chimneys and stacks that vary from about 1 to 25 m in height and 1 to 2 m in diameter. They are composed of Fe, Cu and Zn sulphides. It is estimated that up to 20 000 tonnes of sulphide minerals may have accumulated in the explored part of the axial graben within the past 100 years. The sulphide chimneys show marked zoning outward from pyrrhotite, pyrite and chalcopyrite, to copper-iron and zinc sulphide, to zinc sulphide and marcasite associated with anhydrite and amorphous silica. The zoning sequence is not consistent in all of the chimneys and stacks. Chalcopyrite in the mineral complexes in the axial zone commonly alters to bornite.

The volcanic rocks that have erupted in the axial graben are olivine plagioclase tholeiites that are low in TiO_2 and alkali constituents. These rocks have high FeO/MgO ratios and may be derived from magmas where there has been little differentiation (Hekinian and Fouquet, 1985; Gente et al., 1986).

Seamounts
MN-128 12°49'N 103°53'W 12°42.5'N 103°52'W

Seamounts at these locations, about 6 km east of the axial zone of the East Pacific Rise, are about 6 km in diameter and 400 m in height and cover much of the linear structure on the flank of the ridge. Extensive hydrothermal deposits are present on the slopes and summit of the southeast seamount which may contain ten times more material than that found in the adjacent axial segment of the ridge. The hydrothermal material consists mainly of ocherous iron hydroxide (goethite) and makes up 62 % of the sample recovered. It coats iron-rich massive sulphide (24 % of the sample), silica-rich sulphide (13 %), and massive iron-copper sulphide (1 %). Local patches of cobaltiferous pyrite were found in the silica-rich facies and in massive iron sulphides.

The base of the southern flank of the seamount is blanketed with ocherous sediment that is less than one metre thick which covers about 80 % of a large area of pillowed volcanic flows. The ocher consists of dark iron-manganese scoria-like material that covers yellow to red masses of goethite and limonite. Another area blanketed with ocher extends 500 m upslope from the basal deposit. It is about 200 m wide and 60 to 80 m high and covered with altered hydrothermal products, gossan, and outcrops of sulphide minerals. The 200 by 800 m area at the top of the seamount above the 2450 m contour is covered by hydrothermal deposits about one metre thick that overlie pillow basalt. They consist of altered debris, chimneys and stacks that show zoning of iron, copper, and zinc sulphide minerals. The oxidized phases of sulphide contain covellite in silica-rich samples and chalcocite and covellite in goethite and limonite. The hydrothermal sulphide and oxide deposits from the seamount and the axial zone of the ridge contain 0.3 to 31.6 % Cu, 0.03 to 41.7 % Zn, 15 to 45 % Fe, 21 to 47.7 % S, and a significant content of Pb, As, Ag, Se, Co, Ni, Cd, Sr (Hekinian and Fouquet, 1985).

Larson's Seamounts
MN-129. 20°48'N 109°23'W
Red Volcano,
20°48'N 109°17'W
Green Volcano

Red Volcano located about 30 km west of the axes of the East Pacific Rise has a caldera about 2 km in diameter partly enclosed by a caldera wall 150 m high. Patches of red oxide minerals are concentrated on small peaks at the caldera margins and seepage of warm water was observed from one small fragile chimney. Small cones of pillow lava are mantled by red and orange mud and poorly cemented oxide sediment (Lonsdale et al., 1982).

Green Volcano located about 11 km west of the axis of East Pacific Rise has large deposits of copper-rich polymetallic sulphides within the caldera and on the summit benches. The 800-m-high seamount is similar to Red Volcano in size and shape. Sulphide deposits consisting of pyrite and chalcopyrite were found on the caldera floor, at the walls of the caldera and in the pit craters. Columns and mounds 1 to 3 m high occur in clusters on the sediment-covered lava. The steep slope of the wall of one of the two central pit craters is covered by a blanket of ocherous oxide sediment in which rounded boulders of massive crystalline sulphide minerals are embedded over a distance of 1.5 km (Lonsdale et al., 1982; Levin and Lonsdale, 1983).

21° North, East Pacific Rise
MN-129 20°50'N 109°06'W

A high temperature hydrothermal field with "black smoker plumes" and small but varied sulphide deposits was discovered along the axis of the East Pacific Rise in this area (Lonsdale et al., 1982).

MN-129 20°52'N 109°02'W
20°56'N 109°05' W

Sulphide deposits in the 21° North area on the East Pacific Rise were discovered in 1978 by the joint French-American-Mexican project RITA using the submersible Cyana. They are similar in many ways to the sulphide deposits in ophiolite rocks on Cyprus in the Mediterranean Sea. Active hydrothermal vents and sulphide occurrences were found 700 m west of the axis of the Rise in an area 90 km north of the Rivera and 240 km south of the Tamayo transform fault zones at 20°54' N and 109°03' W in water depths of approximately 2620 m. The deposits form conical and tubular structures that rest on basalt basement rocks and are composed of two main types of material. The polymetallic sulphides consist mainly of pyrite and marcasite associated with zinc and copper-rich mineral phases. The iron oxide and hydroxide phases are rich in goethite and limonite. Silicate phases such as opaline silica, iron-silica clay, and trace amounts of mica and zeolite are encountered in both types of material (Hekinian et al., 1980).

Active high temperature hydrothermal vents and sulphide occurrences were discovered from the submersible Alvin in 1979 along the Ridge axis in a 7 km by 100 m area to the south around 20°50' N and 109°06' W (Hekinian, 1982).

Separation along the East Pacific Rise in this area has been taking place at a constant rate of 3 cm/a during the past 4 million years. The ridge crest area is dominated by a central zone of volcanic hills about 2 to 5 km wide flanked on either side by a zone of open fissures. The sulphide occurrences in the northern area are situated 700 to 800 m west of the axis of the ridge on the flanks of steep-sided structural depressions 20 to 30 m deep and 20 to 30 m wide. The active spreading part of the ridge is about 1.5 km wide and consists of a fissured and faulted terrain of horsts and grabens.

The sulphide occurrences form cylindrical mounds up to 10 m high and averaging 5 m in diameter and are aligned in rows at intervals of 3 to 4 m. The sulphide mounds and edifices are covered by red, white and dark grey porous ocher. Sediment surrounding the hills is made up of reddish-brown, yellow-red and dark grey friable material derived from erosion of the conical hills. Fragments of volcanic glass associated with the sulphide minerals and ocher show no signs of alteration (Hekinian et al., 1980).

Sulphide phases are well crystallized in cubes, tetrahedrons, spheroids and bipyramids and have lath-like, reniform and globular textures. Pyrite and marcasite make up 50 per cent of the samples, zinc sulphide about 34 per cent, and copper-rich minerals about 16 per cent. Sulphide fragments show tubular structures with prominent concentric zoning or lamellae consisting of: gel-like zinc sulphide with the composition of wurtzite; crystalline pyrite and/or sphalerite; hydrous iron oxide; amorphous silica; and iron and silica-rich clay. The massive parts of the samples consist of sphalerite, pyrite and chalcopyrite. Analyses of the bulk samples indicate up to 10 % SiO_2, 49 % Zn, 45 % Fe, 1.5 % Cu, 52 % S, 480 ppm Ag, 640 ppm Pb, 700 ppm Cd, and 500 ppm Co (Hekinian et al., 1980; Francheteau et al., 1979).

Active hydrothermal vents and sulphide occurrences were found in 1979 along the ridge axis in the southern part of the area centred around sites at 20°50'N and 109°06'W by project RISE using the submersible Alvin. Vent fluids emerging from the sulphide chimneys formed black and white plumes as they mixed with seawater. Vent structures consisting of mounds 15 to 30m in diameter and up to 2 m high are surmounted by pipe-like chimneys 1 to 5 m high. Samples collected from the mounds, chimneys and surrounding sediment consist of sulphide and sulphate minerals and fresh basaltic glass. The temperature of the hydrothermal solutions at the Black Forest and two other vent sites was about 350° C and lower at the other vents sampled.

The interiors of the vent chimneys are lined with chalcopyrite and minor amounts of pyrite and the exterior layers consist of black, fine grained pyrite, chalcopyrite and wurtzite mixed with white anhydrite, talc, chrysotile and silica-bearing minerals. Some of the chimneys contain bornite and chalcocite in solid solution and samples from the base of some vents have Fe/Cu ratios between 1 and 2 and contain very little zinc. Samples from a chimney venting solutions at 350° C consist of alternating compact layers of black wurtzite and golden-yellow cubanite sulphide and outer layers that are rich in iron, possibly pyrrhotite.

Samples from a lower temperature (273° C) vent are rich in zinc sulphide and almost devoid of copper minerals and consist mainly of acicular fine-to coarse-grained crystals of anhydrite coated by wurtzite. Another sample from a vent area consists of fine-grained mixtures of wurtzite, pyrite, anhydrite and barite cut by seams of wurtzite underlain by copper-bearing sulphide minerals. Silica is present in the extinct vents as hydrated amorphous silica, in nontronite clay and in minor quantities in zeolites and muscovite. Amorphous silica, talc, chrysotile, aluminosilicates and other silicate minerals are found around the active vents. The salinity of the hydrothermal solutions suggests that they consist of seawater that has reacted with hot basalts below the vents. The isotope composition of the sulphur in the sulphide minerals suggests that the sulphur was derived from basaltic magma and from seawater sulphate. The sulphur in anhydrite is essentially identical to that in seawater (Styrt et al., 1981).

Gulf of California, Baja California Peninsula and Guaymas Basin

The Gulf of California is formed by a complex rift zone at the boundary of the Pacific and North American plates where the East Pacific Rise extends northward to connect with the San Andreas fault system. Separation of the Baja California Peninsula from mainland Mexico is taking place at the rate of 5 to 6 cm/a along a complex series of en echelon spreading axial segments that are offset by transform faults of considerable length (Koski et al., 1985).

MN-130 22°47.34'N 107°59.57'W
22°46'N 107°57' W
22°52.59'N 108°44.84'W
22°44.92'N 107°59.23'W

Gulf of California Basalts from these sites at the mouth of the Gulf of California are interlayered with sediment and smectite mud and are highly altered with veins and vesicules filled with smectite, carbonate, sulphide, and zeolite minerals (Lewis et al., 1979).

MN-131 27°10'N 111°25'W

Guaymas Basin. The Guaymas Basin located along the spreading system in the Gulf of California has two en echelon troughs 3 to 5 km wide that trend 035° that are separated by a transform fault more than 20 km long. The troughs are situated on fast spreading segments of the rift fault system. Hemipelagic sediments consisting of nannofossil-bearing diatom ooze, terrigenous silty mud and turbidite mud are accumulating at rates of 1000 to 2500 mm per year in troughs of the basin. Extensive hydrothermal effusive activity associated with the spreading centres and fault systems in the north and south trough areas has formed deposits of iron-rich talc, pyrrhotite, sulphide minerals, smectite muds and petroleum in the sediments (Stout and Campbell, 1983).

MN-131 27°17'N 111°30'W

Northern Trough, Guaymas Basin. Extensive ledges and terraces encrusted with iron and manganese oxide and white talc that contains iron sulphide were sampled in the southwest part of the northern trough of the Guaymas Basin. Some of the hydrothermal deposits occur along faults of the step-faulted rift wall. The samples are described as hydrothermal sinter and contain siliceous microfossils, smectite, euhedral pyrrhotite and iron-rich talc and sulphur. Oxygen isotope data indicate precipitation of this material at about 280° C. The monominer-

allic iron-rich talc contains silica derived from diatoms, impurities of ferric hydroxide which give the talc the appearance of ocher and patches of pure amorphous iron oxide. Thin surface coatings of manganese and iron oxide and some calcium phosphate are widespread on rock surfaces in the area. Analyses of the samples show a high iron and magnesium content in the siliceous talc, and relatively high amounts of Cu, Zn, Co, and Au (Lonsdale et al., 1980).

MN-131 27°02'N 111°24'W

South Guaymas Basin. Sediment in the Southern Trough of the Guaymas Basin is more than 500 m thick and is intruded by a series of basalt sills and plugs that have uplifted the sediment to form low hills. Clusters of mineral deposits formed by hydrothermal discharge consist of talc, smectite and sulphide on the flat turbidite pond of the rift floor. The floor is interrupted by low fault scarps and four small intrarift hills. A drill core shows the following lithology from top to bottom; 32.5 m of diatomaceous ooze, sandy silt, and silty clay turbidite; a 30-m-thick diabase sill; and 204.5 m of hydrothermally altered diatomaceous mud and turbidite sediment. Sediment above the sill shows little alteration but indurated sediment below it contains secondary minerals and shows an increase in the intensity of the hydrothermal gradient at depth where dolomite, albite, chlorite, quartz, epidote, pyrite and pyrrhotite indicate metamorphism as high as green-schist facies at about 300° C (Stout and Campbell, 1983).

More than 100 hydrothermal deposits have been mapped in a small part of the southern trough. They consist of mounds 10 to 100 m in diameter and 10 to 15 m high that have steep sided walls and ridges and pinnacles radiating from them. The mounds are colonized by tube worms that feed on the hydrogen sulphide in the hydrothermal fluids discharged at these sites. Samples dredged from a 200-m bottom section included material from a mound 15 m high and 25 m wide. They consisted of semiconsolidated clay ooze saturated with odorous hydrocarbons that are believed to be of hydrothermal origin, massive sulphide and barite, barite and calcite, talc, opaline silica, and clay-rich sediment cut by fractures filled with barite and sulphide crystals.

Samples of sulphide material show extensive oxidation on surface and consist predominantly of open boxworks and dendritic aggregates of pyrrhotite crystals with porosities prior to oxidation of about 40 to 50 per cent. Interstices in the aggregate of pyrrhotite crystals contain sulphide minerals, calcite, barite, talc, opaline silica, and iron hydroxide minerals. The samples show layering marked by differences in composition and in grain size of the constituents. Sphalerite, chalcopyrite, and galena make up 25 per cent of the sulphide material and are mainly present in the interstices of pyrrhotite grains. Very small amounts of manganese are present which may have been deposited from hydrothermal solutions saturated with manganese sulphide. Iron-rich sphalerite is common and contains inclusions of chalcopyrite and textural evidence indicates that the common order of sulphide deposition was galena, pyrrhotite, sphalerite, and chalcopyrite. On oxidation the pyrrhotite is replaced by lepidocrocite and goethite and mixtures of these minerals with amorphous iron hydroxide.

Some of the samples consist mainly of barite, and intimate mixtures of barite, calcite, talc, opaline silica and diatomaceous ooze. Porous material is saturated with aromatic petroleum fluid. Fractures in this material are filled with drusy barite crystals and intergrowths of sphalerite, chalcopyrite, galena, digenite, and pyrite in framboids, and appear to mark the conduits along which hydrothermal fluids passed through the sediment. Sediment adjacent to the fractures is darker due to the presence of iron oxide minerals, diatom forms have been destroyed and detrital clay, quartz, and feldspar show little apparent alteration. Talc is a minor phase in sulphide-rich fragments and consists of white honeycombed aggregates of flaky crystals that contain sphalerite and pyrrhotite. Opaline silica is present in many sulphide samples and on a microscopic scale consists of silica fibres forming globules and cellular material that encloses pyrrhotite. Sulphide samples are reported to be composed mainly of iron and sulphur with significant amounts of zinc, copper, lead and manganese and relatively low amounts of silver and cadmium, and variable amounts of lead (Koski et al., 1985).

Simoneit (1985) reports that hydrothermal petroleum in Guaymas Basin is derived from immature, primarily marine, organic matter at depth in the sediments through thermal alteration and rapid quenching brought about by removal in hydrothermal fluids, followed by condensation on the seabed in the mineralized sediment. Significant accumulations of petroliferous exudate in Guaymas Basin indicate the importance of hydrothermal pyrolysis of immature organic matter as a feasible mechanism for the formation of petroleum. Thick sedimentary sequences with structural traps and hydrothermally altered sediment could be significant sources of petroleum in suitable geological settings.

Northeast Pacific Deep Sea Drilling Project Sites 469, 470, 471, 472

Sediments deposited above the basement at these sites are typically reddish-brown, fine grained and enriched in iron and manganese. About 50 per cent of the sediment is composed of amorphous material enriched in Mn, Co, Cu, Ni, and Zn and is similar to that found at other drill sites in the Eastern Pacific. Basal sediments from the area have been described as follows:

MN-132 — 23°00'N 114°00'W, site 472A, age 15 to 17 Ma: Iron-oxide-rich dolomitic nannofossil ooze from core immediately above basalt basement.

MN-133 — 23°29'N 112°30'W, Site 471A, age 13 to 15 Ma: dusky yellow brown iron-rich clay recovered from between sulphide-bearing sediment and black quartzose chert, and associated with highly altered diabase.

MN-134 — 28°55'N 117°31'W, Site 470A, age 15 to 17Ma : pale olive dolomitic claystone above basalt basement.

MN-135 — 32°37'N 120°33'W, Site 469, age 16 to 18 Ma: reddish brown dolomitic iron-rich clay above basalt basement, interbedded with basalt breccia.

MN-136 — 37°7'N 127°33'W, Hole 32, age 34 to 38 Ma: consists of nannofossil "red clay" with some dolomite rhombs immediately above basalt basement.

MN-137 — 40°59'N 130°7'W, Hole 36, age 7-11 Ma: light olive grey nannofossil clay above basalt.

The sulphide bearing sediment at site 471A may have formed near 21°N in the axial part of the East Pacific Rise in the same relative position as the present active hydrothermal vents and subsequently been moved away from the axis as the ridge developed (Yeats et al., 1981).

The sulphide layer from top to bottom consists of:
1) pyrite, chalcopyrite, and zinc sulphide in chert and calcite gangue, about 35 cm thick;
2) metalliferous sediment layer, 5 cm thick; and a
3) chert layer 4 cm thick. The sulphide layers overlie chloritized basalt, diabase and gabbro (Devine and Leinen, 1981).

Near Mendocino and Murray Fracture Zones

MN-138 40°59'N 140°43'W
water depth 4882 m
38°42'N 140°21'W
water depth 5137 m

MN-139 32°48'N 139°34'W
water depth 4929 m

Cores of metalliferous sediment from these sites consist of amorphous iron and manganese hydroxides, iron-rich montmorillonite, goethite, and crystalline iron and manganese hydroxides. The sediments contain 19 to 22% Fe, 5.6 to 7.6% Mn, 6.5 to 8.9% Si, 0.1 to 1.5% Ba, and are enriched in Cu, Ni, Co, Cr, and some of the rare earth elements (Dymond et al., 1973).

MN-140 41°N 141°W (DSDP Site 37)

MN-141 38°N 141°W (DSDP Site 38)

MN-142 32°48.28'N 139°34.29'W (DSDP Site 39)

Basal metalliferous sediment was cored at these sites on a north-south section across major fracture systems in the North Pacific. Site 37 is north of Mendocino Fracture Zone, Site 38 to the south, and Site 39 is in an area of abyssal hills north of Murray Fracture Zone some distance to the south. Three distinct facies were found at the three sites; a basal amorphous iron-manganese oxide facies, a mixed amorphous iron-manganese oxide and detrital facies, and a detrital facies. Lithological sequences of yellow to dark brown, iron- and manganese-oxide facies muds are similar at these sites and may have been deposited in a large basin as one sedimentary succession.

The basal facies at Sites 37 and 39 is 5 to 6 m thick and is described as dusky yellow to brown amorphous goethite mud. At Site 38 the basal facies is 9 m thick and consists of a mixture of amorphous iron-manganese oxides and calcified Lower Eocene calcareous nannoplankton that is overlain by 6 m of sediment composed entirely of amorphous iron-manganese oxide facies. The basal facies lacks detrital sediment and consists of iron- and manganese-oxide except for local admixtures of nannoplankton, an ash bed at Site 37 and scattered aggregates of phillipsite clay.

Overlying the basal facies at all three sites is a dusky yellowish-brown sediment composed of a mixture of amorphous iron-manganese oxide and crystalline detrital components. The amount of iron-manganese oxide decreases upward and the detrital material increases toward the top of the section. Detrital constituents include silt-sized quartz, plagioclase, kaolinite, mica and chlorite along with authigenic or hydrothermal montmorillonite, phillipsite and barite and scattered manganese nodules.

The mixed iron-manganese oxide-detrital facies grades to the lighter yellow-brown upper detrital facies which is composed mainly of silt-sized quartz, plagioclase, kaolinite, mica, chlorite, barite and montmorillonite and sporadic occurrences of manganese micronodules.

Fossils are lacking at all three sites. The iron oxide material consists of a mixture of colloidal-size material and microscopic subspherical yellow-brown particles 0.5 to 25 μm in size. The iron-oxide spherules are translucent and amorphous and vary in colour from light yellow to dark reddish brown and the darker material may contain more manganese oxide than the lighter facies. The content of zeolites decreases from 20 to 40 % in sediment at the seafloor to 0 to 5 % in the iron-manganese oxide facies. Altered volcanic ash beds contain more than 50 % phillipsite. Analyses of selected samples indicate up to 27.85 % Fe, 2.82 % Al and a high content of copper, zinc and other minor elements (von der Borch and Rex,1970; McManus et al., 1970).

MN-143 42°30'N 162°08'W

Iron-rich crust and metalliferous sediment are reported by Goldberg and Arrhenius (1958).

Paramushir Island Area, Sea of Okhotsk

MN-144 51°N 155°E
Water depth about 800 m

Investigations of acoustic interference in waters off Paramushir Island in the Sea of Okhotsk showed that a small cone about five metres high was venting hot water in this island arc area (Avdeiko, 1986).

Gorda Ridge

MN-145 41° to 43°N 127° to 128°W

The Gorda Ridge extends north from the Mendocino Fracture Zone to the Blanco Fracture Zone. The spread-

ing zone is offset to the west along the Blanco Fracture Zone and continues north from there to form the Juan de Fuca Ridge system. It is located 160 to 330 km off the coast of Northern California and Oregon. Spreading along the axis of the ridge takes place at the rate of 5.6 cm/a. A ridge 250 m high is located within the rift valley. The northern part of the rift valley near the Blanco Fracture Zone is about 7 km wide but it narrows to 2 km about 24 km to the south. The rift valley is flanked by steep scarps along normal faults and lies 1000 m below the crest of the main ridge in water depths of about 3500 m. Evidence of recent volcanism is found in many parts of the Ridge area (Malahoff, 1981).

MN-145 40°45'N 127°30'W
water depth 3200 m

Escanaba Trough. Samples of sulphide material were recovered from the axial area of Gorda Ridge from the flank of an uplifted dome in the centre of the sediment-filled Escanaba Trough. The samples consist mainly of pyrrhotite with lesser amounts of sphalerite and chalcopyrite. The sulphide minerals are fresh and unoxidized which suggests that they may have come from an active hydrothermal site (Morton, 1985; Abbott et al., 1986).

Sulphide occurrences with a high content of copper and zinc were found by United States Geological Survey geologists in a large (1 km by 3 km) active hydrothermal field in this area (communication to Geological Survey of Canada).

MN-145 42°08'N 127°09'W

Manganese and iron oxides and nontronite clay were recovered from this area which suggest recent hydrothermal activity (Gray and Kulm, 1985; Clague et al.,1984).

MN-145 42°30'N 126°52'W

Samples of basalt from this area contain small crystals of pyrrhotite, pyrite, sphalerite, and barite(Gray and Kulm, 1985; Duane, 1982).

North Gorda Ridge
MN-146

Abundant evidence has been found of hydrotherrmal venting in the northern part of the Gorda Ridge (Rona and Claque, 1986).

MINERAL OCCURRENCES IN THE JUAN DE FUCA RIDGE SYSTEM

Juan de Fuca Ridge System
44°10'N to 51°30'N , between 128°30'W to 131°30'W

The Juan de Fuca Ridge System as defined here includes a number of related structural segments that extend northward from the Blanco Fracture Zone at 44°10'N and 130°30'W to the Queen Charlotte Fracture Zone at 51°40'N and 130°40'W. Spreading takes place along this fracture system at a rate of about 6 cm/a. The ridge system is divided into a number of structurally complex segments that are defined for general reference as;

a) the Southern segment that extends north on the ridge axis from Blanco Fracture Zone to 45°03'N;
b) the Central segment extending north to 46°30'N;
c) the Northern segment extending to 49°N at the Sovanco Fracture Zone, which includes the Cobb offset and the Endeavour segment in the northern part;
d) the Explorer Ridge segment extending from the Sovanco fracture zone to the Paul Revere Ridge and fracture zone at 50°30'N; and
e) the Dellwood Knolls and J.Tuzo Wilson Seamounts segment.

Blanco Fracture Zone
MN-147 44°10'N 130°W

Core samples from a deep (up to 4800 m) gorge at the intersection of the Blanco Fracture Zone and the Juan de Fuca Ridge consist of layered sediments of unusual colour that have a manganese content of 30 to 100 times greater than that in other sediments in the Northeast Pacific and also show enrichment of 5 to 10 times in the content of As, Cu, Zn, and Ni. The sediment is considered to be of hydrothermal origin and individual layers are believed to correspond to periods of vent activity which probably lasted from 100 to 2500 years (Selk, 1982; Embley et al.,1982).

Southern Segment, Juan de Fuca Ridge
MN-148 44°28'N to 45°03'N 130°22'W

The Southern segment extending north from the Blanco Fracture Zone forms a narrow linear rift zone about 3 km wide that is offset by three en echelon faults with left hand displacement. The average depth of the rift valley is about 2260 m with relief along the boundary faults of 100 m. Most of the rift valley floor is covered by volcanic flows along its 60 km length. Hydrothermal activity is present along the southern 20 km of the rift valley which is totally covered by sheet flows (Embley et al., 1983).

The southernmost section of the rift zone was surveyed in detail for about 35 km, from 44°36.5'N to 44°43'N, and samples of the basalt lava and sulphide deposits were obtained from six active hydrothermal vent areas (Normark et al., 1983). The vent areas occur in a relatively continuous depression in the centre of a smooth 1 km wide valley along the ridge axis. The depression appears to be formed by collapse of a lava lake and modified by extensional faulting. This segment of the ridge is characterized by a straight axial valley 80 to 100 m deep with no lateral offsets; the ridge zone, about 20 km wide, is remarkably symmetrical in cross section. The inner valley walls are formed by steep normal faults and low terraces about 30 m above the valley floor.

The axial valley floor reaches its highest point near 44°38'N in the area where active hydrothermal venting and sulphide deposition is taking place. A narrow depression about 50 to 200 m wide and 25 m deep bounded by sharp rims is continuous along the central part of the valley and appears to have formed by the collapse of a

lava lake. The valley floor is covered by lava flows with pahoehoe-textured and striated surfaces that contain collapse pits and fissures. About half of the lava consists of sheet flows, 25 per cent are pillowed and 25 per cent are lobate and hollow lobate flows. The lavas in the axial valley are 2000 to 200 years old or even younger and those on the flanks of the ridge are 15 000 to 20 000 years old. Glassy selvages on the massive iron-rich basalt contain plagioclase, clinopyroxene and olivine phenocrysts and other thin selvages consist of palagonite and manganese oxide. Many of the lavas are coated with iron and manganese oxide.

Four of the vent areas are within the central depression and another occurs at the base of the scarp along the east wall. The hydrothermal deposits form ledges and shallow mounds in the central axial zone and the vent areas are marked by the abundance of tube worms, clams, benthic siphonophores and other fauna.

Two types of sulphide mineral aggregates were dredged from an active vent site at 44°40'N and 130°22'W. The first consists of angular slabs of dark grey, zinc-rich sulphide with interlayers and a thin oxidized crust of iron sulphide. The layered sulphide aggregates appear to be fragments of a sulphide wall that enclosed an active hydrothermal vent. They are composed of colloform iron sulphide and sphalerite with a low content of iron that was deposited under low temperature conditions. A mineral assemblage inside the wall consists of granular iron-rich sphalerite, wurtzite, pyrite, and copper-iron sulphide. Zonation from iron-rich to iron-poor zinc sulphide from the inside to the outside of the vent wall may result from late stage cooling or a change in fluid chemistry. As temperatures increase, earlier formed minerals dissolve and zinc, iron and lead migrate toward the outer sulphide wall. Microscopic examination shows that sphalerite is the dominant sulphide mineral and forms delicate banded colloform and subhedral granular crystals with broadly zoned hexagonal crystals of wurtzite in the cavities. Galena and chalcopyrite-cubanite are intergrown with sphalerite and wurtzite, and pyrite and marcasite have colloform and granular texture. Abandoned worm tubes composed of pyrite and silica are partly or completely filled with colloform zinc and iron sulphide.

The second type of sulphide material has 35 to 40 % porosity, irregular cavities, and is composed of dendritic aggregates of pale-brown to colourless sphalerite and minor disseminated pyrite, opaline silica and barite. This type of sulphide was deposited at moderate to low temperatures and hematite, barite and sulphur were deposited in late stages when fluids became more oxidizing. The late sulphides are believed to have been formed in areas peripheral to the main discharge vents or even by precipitation on the surface of the lava flows (Koski et al., 1984).

Hydrothermal Plumes over Southern Juan de Fuca Ridge

Extensive surveys have been carried out in the southern area of the Juan de Fuca Ridge to define the nature and distribution of hydrothermal plumes and the dispersal of particulate matter originating from the hydrothermal effusive activity along the ridge axis. Observations show that vent emissions create a particle distribution that is vertically stratified and that varies along the axis of the ridge. Hydrothermal particles are effectively transported off the ridge axis and settling of suspended particles is slow enough to enable individual plumes to coalesce to form uniform clouds at distances of 20 to 100 km from the ridge crest. Mineral particles, mostly of colloid size (10^{-5}-10^{-7} cm) originating in hydrothermal plumes emanating from seafloor vents, may be transported as much as 100 km from the source vents and accumulate as metalliferous sediments in distal basins (Baker et al., 1985).

Central Segment Juan de Fuca Ridge.
45°03'N to 46°30'N

The Central segment is offset about 3 km to the west of the Southern Segment and is 2300 to 2400 m deep, about 6 km wide with boundary fault scarps that are about 20 m high. A prominent central ridge with 80 to 100 m relief extends north to 45°30'N and an area around a split volcano at 45°12'N has fresh sheet flows of lava and low temperature hydrothermal deposits. From 45°30'N the rift zone curves westward toward Axial Seamount centred at 45°59'N 130°03'W and the axial zone is not clearly defined beyond 45°42'N. A prominent shoal spur extending southeast from Axial Seamount may mark a third rift zone which is structurally complex and may be linked to the seamount structure and close to the hotspot centre in the area (Embley et al., 1983).

Axial Seamount
MN-149 45°59'N 130°03'W

This submarine volcano at the intersection of the axial valley and the Cobb-Eickelberg Seamount chain has a large caldera at its crest which is about 6 km long, 4 km wide and about 140 m deep that is open or breached to the south. The relatively flat floor of the caldera at a water depth of 1540 m is covered by sheet flows and there is extensive fissuring and faulting at the intersection of the northern caldera wall and the spreading axis. An extensive hydrothermal field located at the base of the southwest wall has a large number of separate active vents, with water temperatures ranging from 30° C to 293° C, surrounded by a profuse assemblage of fauna where more than 14 new species were identified. Both black and white plumes or "smokers" exhale from chimneys up to 10 m high and orange coloured halos of minerals have been precipitated from the hydrothermal fluids (Chase et al.,1985).

Red-brown sediment is distributed along the axial crest of the ridge system and on the north side of Axial Seamount. It consists of a mixture of nontronite clay, amorphous iron oxide and silica and fills fissures and depresions and coats the fresh lava flows (Malahoff et al., 1984; McMurtry et al., 1984).

An area north of the caldera about 400 m wide has fissures 2 to 10 m wide and 1 to 20 m deep that contain pelagic sediment 20 cm thick. The northwest floor of the caldera has a thin layer of sediment on the glassy basalt and older pillow basalt; relief over the collapsed roofs, hollow basalt columns, cavities and buckled sheet flows is about 5 m. A major fissure extends south across the caldera floor from the fissured part of thenorth wall for about 300 m and terminates at a vertical wall. The fissure is formed by a series of depressions 15 to 25 cm wide, 30 to 35 m long and 5 to 20 m deep; hydrothermal activity was observed in three areas along the northern part of the fissure where temperatures of 35° C were measured in cavities of mounds that are covered by a profusion of worms and fauna. Three chimneys east of the fissure composed of sulphide and sulphate minerals were up to 12 m high and a pagoda-shaped edifice wasventing water with a temperature of 19° C (Chase et al., 1985).

Samples of the chimneys have a spongy texture and consist of the following major minerals in relative order of abundance; barite, amorphous silica, sphalerite, and marcasite; minor minerals are wurtzite, pyrite, and anhydrite, and small amounts of galena, copper-iron sulphides and tetrahedrite. Analyses of the samples show: 10 to 28 % Zn, 3 to 5 % Fe, 0.1 to 0.3 % Cu, 0.6 to 0.1 % Pb, 14 to 15 % Ba, 20 to 41 % SiO_2, 34 to 233 ppm Ag, 110 to 740 ppm Cd, 45 to 32 ppm Mo, 32 to 11 ppm Ni, and 470 to 1300 ppm Mn (Chase et al., 1985).

Samples from a silica-barite-sphalerite chimney in the caldera contain up to 6700 ppb gold and average 4900 ppb (Hannington et al., 1985).

Northern Segment of the Juan de Fuca Ridge System and Endeavour Ridge
46° 30'N to 49°N

The Northern Segment of the Juan de Fuca Ridge system extends from 46°30'N, an area north of Axial Seamount, northward across the Cobb Offset Fracture Zone to its intersection with the Sovanco Fracture Zone near 49°N. The part of the ridge system south of the Cobb Offset is referred to as the Northern Segment of Juan de Fuca Ridge and the part to the north as Endeavour Segment of the main ridge system.

The Cobb Offset forms a broad, northeast trending transform fracture zone along which the Northern and Endeavour ridge segments overlap and are offset about 32 km with lefthand lateral displacement. The axis of recent spreading on the southern part of the ridge follows the normal ridge trend of 20° northward to 47°15'N where it veers north to the Cobb Offset zone. The axial zone of the north segment follows the normal 20° trend but veers south as it approaches the Cobb Offset zone. There is a transition in the morphology of the ridge segments as they approach the offset zone. V-shaped valleys and hills of low relief mark the symmetrical central axial highs along the normal ridge structures. These valleys merge into graben-like depressions near the offset zone where sediments are tilted and disturbed. Evidence of recent volcanism was found in both the Endeavour and Northern segments of the ridge.

Ridge development can be interpreted in two different ways. The first indicates that the Cobb Offset has evolved by a series of northward and southward events of propagation with net advance to the north. The second interpretive model indicates stable asymmetric spreading from overlapping ridge segments that evolved into a transform fault offset by gradual destruction of part of the northern ridge (Johnson et al., 1983).

Geothermal areas
46°50'N 129°20'W

Water temperature and salinity data indicate that there are four anomalous geothermal areas spaced at intervals of 100 km between the Cobb Offset and the Blanco Fracture Zone to the south. The geothermal areas may extend for 20 km along the axial zone of the spreading ridge and are located over morphological domes that rise 100 to 200 m above the floor of the rift valley. Two of the thermal areas to the south that have sulphide deposits and active hydrothermal vents have been described.

The third area is about 100 km north of Axial Seamount at 46°50'N and 129°20'W. In this area the rift valley is about one kilometre wide and the floor is covered with sheet flows and the valley margins are composed of small volcanic cones truncated by fault scarps that parallel the flanks of the axis. A split volcano is located on the shallow domed part of the valley floor and the fault margins of the valley are linear (Crane et al., 1985).

MN-151 47°35'N 129°W

The axial valley narrows to about 0.5 km along the 100 km of ridge between the last hydrothermal site and this geothermal location where the axial valley is dominated by a large split seamount that rises about 450 m above the axis of the ridge.

47°33'N 128°57'W

Iron-rich nontronite clay mixed with manganese oxide of hydrothermal origin was dredged from this site on the north side of the Cobb Offset and about 2.5 km west of the projected axis of the southern segment of the ridge. Spreading is taking place in this area at the rate of 6 cm/a. Low, well-rounded hills are surrounded by indurated sediment. Fragments of fresh pillow basalt and green clay with a dark brown crust were recovered from this site. The friable green clay fragments were up to 10 cm thick with layers up to 7 cm thick. Layers of brown crust are 1 to 3 cm thick with orange patches of amorphous iron oxide and numerous cavities and worm tubes.

The pure clay layers are dark olive-green to yellow-green and consist of well crystallized nontronite with the usual amounts of ferric iron in the tetrahedral and octahedral sites of the crystal lattice. Some of the samples that are similar to turbidite sediment in the Cascadia basin contain todorokite and birnessite (manganese oxide minerals), some of the samples contain quartz, plagioclase, amphibole, chlorite, and illite, and some contain

montmorillonite. The clay samples contain up to 52 % SiO_2, 0.3 to 6.7 % Al_2O_3, 21 to 33 % Fe_2O_3, 0.04 to 11 % Mn, up to 5 % $K_2O + Na_2O$, and a significantly high content of Ba, Zn, Cu, Ni, Rb, Sr, rare earth elements, and other minor elements that are typical of modern hydrothermal clay sediments and the older iron-formations and stratafer chemical sediments (Murnane and Clague, 1983).

Endeavour Ridge Segment
47°30'N to 49°N

The Endeavour Ridge segment extending north from the Cobb Offset to the Sovanco Fracture Zone is divided into two ridge sections by the Endeavour Seamount at 48°10'N and 129°10'W, which occupies the middle of the Endeavour Offset zone, an overlapping spreading centre about 13 km wide. Spreading occurs along the entire ridge segment and is marked by a narrow (1 to 2 km) valley superimposed on broader shallow valleys and volcanic ridges 5 to 10 km wide at water depths of 2100 to 3000 m. Active spreading on the southern section of Endeavour Ridge transfers to the West Valley in the Endeavour Seamount area and continues north to the Sovanco Fracture Zone. The southern section is traced northward along the east side of the Endeavour Offset where it forms Middle Valley, a deep, sediment-filled trough along an older failed rift system.

The valley of the southern section of the ridge is well defined by continuous fault scarps and fissuring and is dominated by lightly sedimented young lobate and pillow flows. The flanking ridge is capped with older pillow lavas and sediment (Karsten et al., 1986).

MN-152 47°56'N 129°08'W
South Section Endeavour Ridge. Vent sites are located along the western wall of a graben within a perched basin about 40 to 50 m above the floor of the axial depression. The basin appears to have formed between a hanging wall and a back-tilted downdropped fault block. The site is dominated by several 15-to 20-m-high "black smoker" sulphide chimneys and fissures that are marked by a large number of tube worm colonies. The area bordering the vent site has relatively low temperature vents and extensive deposits of nontronite clay. Numerous sulphide deposits were found nearby on the western wall of the axial valley which lie parallel to the axis of the ridge and appear to be formed by coalesced chimneys.

A high frequency side-scan sonar survey indicates that there are numerous other vent sites along the axis of Endeavour Ridge (Hammond et al., 1984).

The steep sided sulphide structures are up to 30 m in length, 20 m high, 10 to 15 m wide and are distributed for about 200 m along normal faults at the base of the western wall of the axial valley. High temperature fluids (350° to 400° C) discharge through small concentric nozzle-like openings that project from the top and sides of the large sulphide structures. Seepage of low temperature fluid is pervasive from the sulphide structures and basalt surfaces. Evidence of recent volcanism is sparse.

Large samples dredged from the site are complex parts of the sulphide structures and show evidence of sealing of fluid channels. Iron sulphides and amorphous silica are predominant with minor amounts of pyrite, marcasite, wurtzite, chalcopyrite and cubanite. Small amounts of pyrrhotite, galena, and sphalerite are present. Barite, amorphous silica and chalcedony are common non-sulphide phases and anhydrite was found in one sample. More than 40 per cent of the samples are composed of amorphous silica which forms thick colloform coatings on all of the sulphides. The sulphide structures developed in two distinct stages: first, by progressive development of channels to enable the flow of high temperature fluid and the deposition of sulphide minerals in a complex paragenic sequence; and second, by deposition of amorphous silica during the diffuse flow of cooler hydrothermal fluids through the sulphide structures after primary flow channels had become sealed by minerals (Tivey and Delaney, 1986).

The growth rate of the sulphide chimneys has been shown by study of lead isotopes to be 1.2 cm/a. The mineralogy and texture of the samples indicate a nonsequential accretionary growth of the material with considerable remobilization and redeposition of the mineral constituents (Kadko et al., 1985).

Samples of hydrothermal fluids which ranged in temperature from 50°C to 400° C were collected from vent sites in this area at water depths of 2200 m. The fluids have alkalinities higher than seawater and a high content of radon (McDuff et al., 1984).

A hydrothermal plume 200 m above the vent field that extended for several kilometres beyond the ridge area was detected by measuring the temperature and radon content of the seawater (Kadko et al., 1984).

MN-152 47° 57'N 129°06'W
Samples were collected from sulphide structures on the west margin of the valley floor adjacent to the highly fractured and fissured valley wall. The valley floor in this area is covered with sediment and pahoehoe lava flows and evidence of recent volcanic activity was not observed. Hydrothermal activity extends for hundreds of metres along strike at the base of large coalesced sulphide structures up to 18 m high and 30 m in diameter that emerge from deeply fissured lobate basalt terrain. The sulphide structures are heavily colonized by tube worms and other biota. The structures are rich in copper and zinc sulphide and hydrothermal fluids seeping from the sulphide pinnacles have temperatures up to 400° C and have a high chloride content (Johnson et al., 1984; Karsten et al., 1984).

North Endeavour Ridge, Middle Valley
MN-153 48°26.2'N 128°40.6'W

The active spreading axis of Endeavour Ridge is offset to the west in the area south of Endeavour Seamount and extends north through West Valley to Sovanco Fracture Zone. Middle Valley extends northeast from the Cobb Offset zone along strike from the southern section of

Endeavour Ridge and marks part of a "failed rift" system in the main ridge structure. Middle Valley is filled with a thick sequence of turbidite sediment. Seven mounds a few hundred metres in diameter and rising 60 m above the flat sediment-covered valley floor are located along the east side of Middle Valley where the water depth is about 2400 m. The mounds have simple to complex morphology, show diffuse seismic profiles, are the site of anomalously high heat flow and are associated with hydrothermal and noncalcareous indurated sediments. The mounds have formed above a sequence of lutite and clastic sediments that is about 200 m thick and are composed of sulphide and lutite muds with complex sedimentary and breccia features (Goodfellow et al., 1985; Davis et al., 1987; Adshead et al., 1986).

A core 2.4 m long recovered from one of the mounds consists mainly of alternating beds of coarse-grained clastic sulphide, black sulphide mud, brown lutite mud and sulphide (Goodfellow et al., 1985). The lithology of the various layers from top to bottom is described as:

1) brown hydrothermal mud with rusty clasts of oxidized sulphide up to 5 mm in diameter;
2) black sulphide mud with streaks of barite and talc and small clasts of sulphide that are sand-size at the base;
3) bronze to dark grey-coloured subrounded to angular clasts of sulphide up to 3 cm in diameter in a matrix of sand-sized granular black sulphide;
4) black gelatinous sulphide mud with clasts of sulphide and granular sand with silt-sized sulphide particles;
5) bronze to dark grey-coloured sand-sized sulphide with angular to subrounded sulphide clasts up to 8 cm in size and clasts of medium grey hemipelagic mud;
6) various units consisting of bronze to dark grey angular clasts of sulphide in a matrix of finer grained dark grey sulphide;
7) black granular sulphide mud.

The sulphide-rich parts appear bedded and range in grain size from the black sulphide-bearing mud to coarse grained sulphide fragments. Microscopic textures show that sulphide fragments are cemented with talc, overgrown by pyrrhotite and recemented by talc. They consist mainly of granular aggregates of pyrite and pyrrhotite with variable amounts of sphalerite, chalcopyrite, isocubanite, marcasite and galena in a matrix of barite, amorphous silica and talc. The sulphides form a coarsely crystalline network of hexagonal pyrrhotite grains rimmed by pyrite; pore spaces are filled with sphalerite. The sphalerite and pyrrhotite are overgrown by chalcopyrite and isocubanite and the sulphide crystals are intermixed with clusters of euhedral barite crystals. Analyses indicate that the sulphides contain 2.7 to 4.6 % Zn, 0.23 to 0.41 % Cu, 1.1 to 7.5 ppm Ag, 43 to 165 ppm Mo, 119 to 158 ppb Au, 0.13 to 3.10 % Ba, 2.2 to 7.10 % MgO, 134 to 248 ppm As, 20 to 46 ppm Sb and 81 to 136 ppm Se (Goodfellow et al., 1985).

A core of sediment recovered from 2.4 m beneath the surface of a mound described by Adshead et al. (1986) consists of thin, soft, brown bands high in Ba, Mn, and organic carbon that are interbedded with calcareous grey lutite and noncalcareous indurated layers containing soft angular clasts of sediment. The core was composed of the following lithological units;

1) olive grey indurated sediment containing sedimentary clasts, worm burrows, black films of manganese oxide and possibly some sponge spicules,
2) Semi-indurated sediment composed of angular fragments that are soft and friable and set in a matrix of calcareous mud that grades upward into soft lutite mud,
3) soft unlithified clasts are noncalcareous, angular to subrounded and composed of lithified lutite, indurated silt, laminated silt, with some rusty brown coating on clasts,
4) dark brown unlithified bands consist of brown layers interbedded with olive grey lutite, and contain sponge spicules, siliceous biogenic debris and radiolarian tests, silt size clay, detrital silicates, flaky silica and red ferruginous particles,
5) lutite muds typically composed of particles less than 20 um in size.

The sediment contains up to 67 % SiO_2, 17 % Al_2O_3, 7.8 % CaO, 5 % Na_2O, 3 % K_2O, 4 to 5 % Fe, 0.5 % Mn, and a content of trace elements typical of many hydrothermal smectite sediments (Adshead et al., 1986).

Explorer Ridge

MN-154 49°20'N to 50°20'N 130°40'W to 130°20'W

The southern segment of Explorer Ridge extends northeast from its intersection with Sovanco Fracture Zone at 49°20'N and 130°40'W on the northeast side of Explorer Seamount to a northwest-trending fracture zone at about 49°55'N and 130°15'W. Northeast of this fracture zone the main ridge structure divides into two separate sections. The eastern section extends northeast to meet Paul Revere Ridge at 50°08'N and 129°45'W. The western section is further offset to the west at the southeast edge of Dellwood Seamounts before it joins Paul Revere Ridge at 50°20'N and 130°15'W. The ridge is marked by lava flows, rugged topography with cliffs 50 to 80 m high, intensely faulted horst and graben topography, and major northwest-trending faults cutting the northeast-trending axial faults. The area is covered with red to yellow metalliferous sediment.

A central valley about 100 m deep and 1.7 km wide in the southern segment of Explorer Ridge extends for 30 km to the northeast. Water depths in this axial valley rise from about 2000 m in the south to about 1760 m near a transverse fracture zone in the north where the valley merges into an area of low relief. This central valley is paralleled by two adjacent depressions about 250 m wide and 40 m deep which may mark earlier spreading centres. Near latitude 49°40'N the single spreading valley divides into a west valley and an east valley that extend northeast to intersect with a transverse fracture zone. The West valley is heavily covered by sediment overlying older sheet flows, pillowed and oblate flows. The East valley has light

sediment cover over lobate bulbous pillow lavas and lava flows with drain-back features. The main centre of hydrothermal activity is located in the northeast end of the East valley around Magic Mountain at 49°45'N and 130°15'W.

Southern Explorer Ridge, Magic Mountain
MN-154 49°42'N to 49°46'N 130°46'W

About 60 sulphide deposits associated with active vent sites have been found mainly along an 8 km stretch of the east wall of East Valley that extends south from Magic Mountain at 49°46'N and 130°16'W where water depths vary from 1760 to 1800 m. A second large vent field has been located at the north end of the West Valley where altered basalt and metalliferous sediment are found.

The seven large deposits occur near transverse faults and consist of mounds up to 200 m long and 100 m wide and 5 to 10 m thick that are made up of smaller coalesced mounds about 20 m in diameter. The mounds are commonly mantled by or have a weathered aureole of metalliferous sediment and appear to grow by accumulation of sulphide talus from the erosion and collapse of chimney structures and by hydrothermal precipitation from beneath. Many of the domes have been intersected by faults and sections of their interior structures are exposed on cliff faces.

Stratigraphy of the Parizeau deposit from bottom to top is reported to be:
1) stockwork mineralization in pillow lavas,
2) sharp contact with about 10 m of massive sulphide which is copper-rich at the base and zinc-rich at the top,
3) barite rich chimneys and spires, and
4) bright red oxidized metalliferous sediment 1 to 4 cm thick on top of the massive sulphide lenses.

The chimneys are relatively zinc-rich and copper-poor and the massive sulphide lenses are richer in copper while massive lenses in Explorer Ridge generally contain more zinc and barite than at other sites in the East Pacific (Johnson et al.,1984, ; Hannington et al., 1985; Scott et al., 1984)

Mineralogically the mounds consist of 20 % barite, 20 % silica, 20 % sphalerite and wurtzite, 17 % chalcopyrite, 10 % marcasite, 10 % pyrite, with minor copper-iron-zinc sulphide and covellite. Sulphide talus is coated with amorphous iron and manganese, jarosite and atacamite. Analyses of eight sulphide samples show an average content of 9.0 % Zn, 8.1 % Cu, 10.8 % Fe, 0.1 % Pb, 19.2 % SiO_2, 7.9 % Ba, 112 ppm Ag, and 0.6 ppm Au. The mounds are zoned from the base upward from Cu-Fe-rich massive sulphide through Zn-rich massive sulphide to a silica and barium-rich cap. The zoning is analagous to that found in some ancient massive sulphide deposits and may have been developed by hydrothermal reworking of some of the mounds (Hannington et al., 1985).

Hydrothermal Plumes, Explorer Ridge

Hydrothermal plumes near Magic Mountain (49°45.6'N, 130°16.2'W) had particle concentrations up to 160 g/L. The particles consisted of orange brown amorphous Fe-Si-P-S phases with minor crystalline Mg-silicates. Seawater within the plumes contained up to 274 nmole/kg of Fe and 63 nmole/kg of Mn. Two separate plumes were detected. One was associated with a known hydrothermal field and the other is interpreted as originating at the northern end of West Valley about 1.2 km northwest of Magic Mountain. The plumes become intermixed and the combined plume was traced in a westerly direction from Magic Mountain for 8.3 km between 20 and 340 m above the seafloor. Other indications of a plume were found 5.7 km north of Magic Mountain (McConachy et al., 1985).

Explorer Deep
MN-155 50°07'N 129°47'W

Metalliferous sediment was dredged from Explorer Deep in the northeast segment of Explorer Ridge from near the crest of the median ridge at water depths of 3000 to 3200 m. The crust-like pieces of sample are composed of friable orange to black iron-manganese oxides and soft yellow-green clays that are made up of nontronite clay, birnessite and todorokite. Fragments of the sample contain from 15 to 20 % Fe, 15 to 20 % Mn, and up to 151 ppm Zn, 40 ppm Cu, 1200 ppm Ba, 86 ppm Ni, and 40 ppm Cr and are similar in composition to many other metalliferous sediments around hydrothermal fields (Grill et al., 1981).

MN-156 49°40.45'N 131°56.24'W
Basal metalliferous sediment was recovered at the end of 169 cm of core in water depths of 3260 m from the northwest segment of Explorer Ridge. Manganese oxide fragments are abundant in a stiff grey silty lutite that is overlain by dark brown, brownish grey to yellowish brown or olive grey lutite mud. The metalliferous sediment contains quantities of Fe, Mn, Cu, Pb, Ni, Co, and Zn that are very similar to those found in other metalliferous sediments of the Northeast Pacific.

Forty-two cores from the vicinity of the Juan de Fuca and Explorer ridges composed mainly of lutite muds had contents of metal elements somewhat below the average for Pacific pelagic clays. Basal metalliferous sediment was identified in only one of the cores which is described above (Bornhold et al., 1981).

Dellwood Seamount
MN-157 50°45.7'N 130°53'W

An iron-rich sediment dredged from a depth of 600 to 800 m on the northern flank of Dellwood Seamount consisted of red thinly layered, semi-consolidated amorphous hydrated iron-oxide. The material resembles other metalliferous sediment of hydrothermal effusive origin and contains about 30 % Fe, 2 % Mn, 18 % SiO_2, and significant amounts of minor metals and rare earth elements (Piper et al., 1975).

Dellwood Knolls
MN-157 50°50'N 130°30'W

The Dellwood Knolls are two prominent volcanic peaks at the north end of the Juan de Fuca Ridge system about 40 km beyond the base of the continental slope. The knolls rise 800 to 1000 m above the seafloor and the axis of spreading is believed to extend northeast through the valley between the knolls. No clear evidence of hydrothermal vent activity was found but cores consisted of 40 to 50 per cent smectite clay, 20 to 30 per cent chlorite, 10 to 20 per cent illite and interstratified illite and smectite. Minor element content is reported to be below the average for Pacific pelagic clay except for zinc where the mean content is 219 ppm and the maximum is 573 ppm (Blaise et al., 1984).

Tuzo Wilson Seamounts
MN-157 51°28'N 130°50'W
51°25'N 131°02'W

The Tuzo Wilson Seamounts are elongate hills located 50 km south of the Queen Charlotte Islands that emerge through a thick sediment fan on the continental rise at a water depth of 2200 m and rise to a water depth of 1400 m. Alkali basalt fragments from the seamounts have been dated at about 55 000 years. The two knolls are about 25 km southwest of the continental margin and are bounded to the southwest by a fault which is a northwest extension of the Revere-Dellwood Fracture Zone and to the northeast by the Queen Charlotte transform fault. It is believed that the Tuzo Wilson Seamounts are part of a new segment of the Explorer Ridge system that was initiated less than one million years ago.

The seamounts are elongated parallel to a proposed axis where spreading may be taking place at 5.5 cm/a. Major and trace elements in the alkali basalts from the Tuzo Wilson Seamounts are typical of alkaline volcanism on ocean islands associated with mantle plumes. It is suggested that these seamounts may have developed in an area where spreading jumped from the Juan de Fuca Ridge system to a weak area in the crust that was related to the Pratt-Welker mantle plume or hot spot (Cousens et al., 1985; Carbotte et al., 1986).

INFORMATION SOURCES FOR MAP 1659A

1981 — Plate-Tectonic map of the Circum-Pacific Region; M.T.Halbouty, Chairman, Circum-Pacific Council for Energy and Mineral Resources; published 1981, by the American Association of Petroleum Geologists.

1981 — Seismicity of the Earth 1960-1980, (mercator projection, horizontal scale 1:46,460,600), by A.F.Espinosa, U.S. Geological survey, W.Rinehart, World Data Center A, for Solid Earth Geophysics, Marie Tharp, Lamont-Doherty Geological Observatory of Columbia University; 1981; World Ocean Floor Panorama, sponsored by the United States Navy through the Office of Naval Research, Bruce C.Heezen (1924-1977) in memoriam.

1980 — World chart illustrating various limits based on definitions of the outer edge of the continental shelf; (natural scale 1:30,000,000 at equator; projection mercator; spheroid: international); prepared by the Naval Hydrographic Office Dehra Dun, 26 February 1980, under the superintendence of Rear Admiral F.L.Fraser, A.V.S.M., F.I.S., Chief Hydrographer to the Government of India.

1980 — Rona,P.A., NOAA Atlas 3, The Central North Atlantic Ocean Basin and Continental Margins: Geology, Geophysics, Geochemistry, and Resources, including the Trans-Atlantic Geotraverse (TAG); United States Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Research Laboratories.

1978 — Map, Ocean Floor Sediment and Polymetallic Nodules; (horizontal scale 1:23,230,300), by M.D.Rawson and W.B.F.Ryan, in collaboration with P.E.Biscaye, L.H.Burckle, D.W.Cooke, D.Ericson, J.D.Hays, V.Kolla, F.W.McCoy Jr., C.D.Ninkovich, W.C.Pitman III, L.Sullivan, M.Tharp, and G.Wollin; drafted by A. Sotiropoulos, Lamont-Doherty Geological Observatory of Columbia University, Palisades, New York 10964, U.S.A.; sponsored by United States Department of State, Office of the Geographer, 1978. World Ocean Floor Panorama by B.C.Heezen and M.Tharp, 1977.; Sponsored by United States Navy through the Office of Naval Research.

1977 — Map, World Ocean Floor; (mercator projection; horizontal scale 1:46,460,600); by Bruce Heezen and Marie Tharp, Department of Geological Sciences and Lamont-Doherty Geological Observatory of Columbia University, Palisades, New York; based on research and exploration and supported by United States Navy, Office of Naval Research, painted by H.C.Berann, assisted by H.Vielkind; cartographic work by S.B.MacDonald;, 1977-First Edition, Second Printing 1982; Published by the United States Navy as a memorial to Dr. Bruce C. Heezen in recognition of his contributions to man's knowledge of the world ocean floor.

1977 — Map, Nickel plus copper in ferromanganese nodules and crusts from the Northeast Equatorial Pacific; compiled from Scripps Institution of Oceanography Sediment Data Bank, by J.Z.Frazer and M.B.Fisk, September 1977, map scale = 0.56 inches/degree longitude, S10, Ref.No. 77-16.

1974 — World Seismicity Map, prepared by United States Geological Survey, from earthquake data of National Oceanic and Atmospheric Administration, compiled by A.C.Tarr, 1974, Department of the Interior-United States Geological Survey, Reston, Va., 1974-G74119.

1974 — Maps, Manganese deposits in the South Pacific Ocean, (scale 1:25,000,000), Distribution, Miscellaneous Series No.33, Manganese content, Miscellaneous Series No.34, Iron content, Miscellaneous Series No.35, Copper content, Miscellaneous Series No.36, Nickel content, Miscellaneous Series No.37, Cobalt content, Miscellaneous Series No.38, Metalliferous Sediments, Submarine Volcanism and Submarine Geothermal Activity in the South Pacific Ocean, Miscellaneous Series No.39, New Zealand Oceanographic Institute, Wellington, Published by the Department of Scientific and Industrial Research, 1974.

1972 — Horn,D.R., Horn,B.M., and Delach,M.N. Ferromanganese deposits of the North Pacific Ocean; Technical Report No. 1, NSF-GX33616, Lamont-Doherty Geological Observatory of Columbia University Palisades,

New York, Office for the International Decade of Ocean Exploration, National Science Foundation, Washington, D.C. 20050, including —

Map 1, Sedimentary Provinces, North Pacific;
Map 2, Sedimentary Provinces, North Pacific, surface distribution ferromanganese deposits;
Map 3, Sedimentary Provinces, North Pacific, nickel, copper and cobalt content of ferromanganese nodules;
Map 4, Sedimentary Provinces, North Pacific, iron, manganese and calcium content of ferromanganese nodules;
Map 5, Sedimentary Provinces, North Pacific, wet density, porosity and moisture content of the substrate.

1971 — International Geological Map of Europe and the Mediterranean Region; (scale 1:5,000,000), International Geological Congress, Commission for the Geological Map of the World, Published by Bundesanstalt Fiir Bodenforschung and UNESCO, Coordinators: H.-R.V. and H.W.Walther.

1970 — McKelvey,V.E. and Wang,F.H. Preliminary maps, World subsea mineral resources; Miscellaneous Geologic Investigations Map 1-632.

Sheet 1: Petroleum, phosphorite, manganese-oxide nodules, and metal-bearing mud;
Sheet 2: Geologic and physiographic provinces, subsea underground mines, and coastal placer deposits, compiled by V.E.McKelvey, F.H.Wang, P.Quinterno, and S. Hayden;
Sheet 3: Potential petroleum resources, compiled by V.E.McKelvey, F.H.Wang, P.Quinterno, and R.G.Martin Jr.;
Sheet 4: Saline minerals, sulfur, phosphorite, manganese-oxide nodules, and metal-bearing mud, compiled by V.E.McKelvey, F.H.Wang, and T.R.Albha;
The United States Geological Survey, Washington D.C.

SELECTED BIBLIOGRAPHY

Anonymous
1983: Marine Minerals: An alternative mineral supply; National Ocean Goals and Objectives for the 1980's, National Advisory Committee on Oceans and Atmosphere, United States Government Printing Office, Washington,D.C. July 1983, 53 p.

1982: Seabed Minerals, Volume 1, Assessment of manganese nodule resources; Ocean Economics and Technology Branch, United Nations, Graham and Trotman, London. 76 p.

1982: Sea-bed nodules, an alternative source?; Mining Journal, December 3, p.391-392.

Abbott, D.H., Morton, J.L., and Holmes, M.L.
1986: Heat flow measurements on a hydrothermally-active, slow-spreading ridge: The Escanaba Trough; Geophysical Research Letters, v.13, no.7, p.678-680.

Adshead, J.D., Bornhold, B.D., and Davis, E.E.
1986: Indurated deposits and possible plume bands in a hydrothermal mound, northeast Pacific; in Current Research, Part A, Geological Survey of Canada, Paper 86-1A, p.737-748.

Amann, H.
1985: Development of ocean mining in the Red Sea; Marine Mining, v.5, no.2, p.103-116.

Anderson, R.N.
1982: Call Alvin for hot science; Nature, v.300, p.215.

Anderson, T.F., Donnelly, T.W., Drever, J.I., Eslinger, E., Gieskes, J.M., Kastner, M., Lawrence, J.R., and Perry, E.A.
1976: Geochemistry and diagenesis of deep-sea sediments from leg 35 of the Deep Sea Drilling Project; Nature, v.261, p.473-475.

Aoki, S., Kohyama, N., and Sudo, T.,
1979: Mineralogical and chemical properties of smectites in a sediment core from the southeastern Pacific; Deep-Sea Research, v.26A, p.893-902.

Aumento, F., Lawrence, D.E., and Plant, A.G.
1968: The ferro-manganese pavement on San Pablo Seamount; Geological Survey of Canada, Paper 68-32. 30 p.

Avdeiko, G.
1986: Deep underwater volcanic spring found in Sea of Okhotsk; Pravda, 7 February, 1986, p.3

Bäcker, H., Lange, J., and Marchig, V.
1985: Hydrothermal activity and sulphide formation in axial valleys of the East Pacific Rise crest between 18 and 22°S; Earth and Planetary Science Letters, v.72, p.9-22.

Bäcker, H. and Richter, H.
1973: Die Rezente Hydrothermal-Sedimentare Lagerstatte Atlantis II-Tief im Roten Meer; Geologisch Rundschau, v.3, p.397-741.

Baker, E.T., Lavelle, W.J., and Massoth, G.J.
1985: Hydrothermal particle plumes over the southern Juan de Fuca Ridge; Nature, v.316, p.342-344.

Baker, E.T., Massoth, G.J., and Curl, H.C.
1984: The distribution of hydrothermally-derived particulate and thermal plumes over the southern Juan de Fuca Ridge; EOS, v.65, no.45, p.1111.

Ballard, R.D., van Andel, T.H., and Holcomb, R.T.
1982: The Galapagos Rift at 86°W, 5. Variations in volcanism, structure, and hydrothermal activity along a 30-kilometer segment of the rift valley; Journal of Geophysical Research, v.87, no.B2, p.1149-1161.

Bender, M., Broecker, W., Gornitz, V., Middel, U., Kay, R., Sun, S.-S., and Biscaye, P.
1971: Geochemistry of three cores from the East Pacific Rise; Earth and Planetary Science Letters, v.12, p.425-433.

Berger, W.H.
1986: Gumbel's hypothesis regarding the origin of manganese nodules; EOS, Transactions, American Geophysical Union, v.67, No. 14, p.169-179.

Bischoff, J.L.
1969: Red Sea geothermal brine deposits; in Hot Brines and Recent Heavy Metal Deposits in the Red Sea, eds. E.T.Degens and D.A.Ross, Springer-Verlag, New York, p.368-401.

Bischoff, J.L., Piper, D.Z., and Quinterno, P.
1979: Nature and origin of metalliferous sediment in Domes site C, Pacific manganese nodule province; in La Genese des Nodules de Manganese, Colloques Internationaux du Centre National de la Recherche Scientifique, No.289, Editions du Centre National de la Recherche Scientifique, Paris, p.119-138.

Bischoff, J.L., and Rosenbauer, R.J.
1977: Recent metalliferous sediment in the North Pacific manganese nodule area; Earth and Planetary Science Letters, v.33, p.379-388.

Bischoff, J.L., Rosenbauer, R.J., Aruscavage, P.J., Baedecker, P.A., and Crock, J.G.
1983: Sea-floor massive sulfide deposits from the 21°N, East Pacific Rise, Juan de Fuca Ridge, and Galapagos Rift: Bulk chemical composition and economic implications; Economic Geology, v. 78, p.1711-1720.

Blaise, B., Bornhold, B.D., Maillot, H., and Currie, R.G.
1984: Sedimentation near the Dellwood Knolls northern Juan de Fuca Ridge System; EOS, v.65, no.45, p.1112.

Bloch, S.
1978: Phosphorus distribution in smectite-bearing basal metalliferous sediments; Chemical Geology, v.22, p.353-359.

Bloch, S.
1981: Antipathetic magnesium-manganese relationship in basal metalliferous sediments; Chemical Geology, v.33,p.101-113.

Bonatti, E., Guerstein-Honnorez, B-M., and Honnorez, J.
1976: Copper-iron sulfide mineralization from the equatorial Mid-Atlantic Ridge; Economic Geology, v. 71, p.1515-1525.

Bonatti, E., and Joensuu, O.
1966: Deep-sea iron deposit from the South Pacific; Science, v.154, p.643-645.

Bonatti, E., Kolla, V., Moore, W.S., and Stern, C.
1979: Metallogenesis in marginal basins: Fe-rich basal deposits from the Philippine Sea; Marine Geology, v.32, p.21-37.

Bornhold, B.D., Gross, G.A., McLeod, C.R., and Pasho, D.W.
1982: Polymetallic sulphide deposits on ocean ridges; The Canadian Mining and Metallurgical Bulletin, v.75, no.841, p. 24-28.

Bornhold, B.D., Tiffin, D.L., and Currie, R.G.
1981: Trace metal geochemistry of sediments, Northeast Pacific Ocean; Geological Survey of Canada, Paper 80-25, 21 p.

Boström, K.
1980: The origin of ferromanganoan active ridge sediments; in Seafloor Spreading Centers Hydrothermal Systems, eds. P.A.Rona and R.P.Lowell; Benchmark Papers in Geology,v.56, Dowden, Hutchinson & Ross,Inc., Stroudsburg, Pennsylvania. p.288-332.

Boström, K., Joensuu, O., Valdes, S., and Riera, M.
1972: Geochemical history of South Atlantic Ocean sedimentation since Late Cretaceous; Marine Geology, v.12, p.85-124.

Boström, K., Peterson, M.N.A., Joensuu, O. and Fisher, D.E.
1969: Aluminum-poor ferromanganoan sediments on active ocean ridges; Journal of Geophysical Research, v.74, no.12, p.3261-3272.

Boström, K., and Rydell, H.
1979: Geochemical behaviour of U and Th during exhalative sedimentary process; in La Genese de Nodules de Manganese; Colloques Internationaux du Centre National de la Recherche Scientifique, No. 289, Editions du Centre National de la Recherche Scientifique, Paris, p.151-166.

Boström, K. and Widenfalk, L.
1984: The origin of iron-rich muds at the Kameni Islands, Santorini, Greece; Chemical Geology, v.42, p.203-218.

Both, R., Crook, K., Taylor, B., Brogan, S., Chappell, B., Frankel, E., Liu, L., Sinton, J., and Tiffin, D.
1986: Hydrothermal chimneys and associated fauna in the Manus Back-Arc Basin, Papua New Guinea; EOS, Transactions, American Geophysical Union, v.67, no.21, p.489.

Boulègue, J., and Hamelin, B.
1983: Activite hydrothermale de la dorsale Pacifique Est a 21°30'S d'après des profils de concentration du manganèse dans l'eau de mer; Comptes Rendus Academie des Sciences, Paris, v.297, Serie II, p.671-673.

Burns, R.G. and Burns, V.M.
1977: Mineralogy;in Marine Manganese Deposits, ed. G.P.Glasby; Elsevier Oceanographic Series 15, Elsevier, Amsterdam, p.185-248.

Calvert, S.E.
1978: Geochemistry of oceanic ferromanganese deposits; Philosophical Transactions of The Royal Society, London, A.290, p.43-73.

Cann, J.R., Winter, C.K., and Pritchard, R.G.
1977: A hydrothermal deposit from the floor of the Gulf of Aden; Mineralogical Magazine, v.41, p.193-199.

Carbotte, S.M., Dixon, J.M., and Farrar, E.
1986: Geological and geophysical characteristics, and geotectonic significance of the Tuzo Wilson Knolls; Geological Association of Canada, Mineralogical Association of Canada, Canadian Geophysical Union, Joint Annual Meeting, Program with Abstracts, Volume 11, p. 52.

Chase, R.L., Delaney, J.R., Karsten, J.L., Johnson, H.P., Juniper, S.K., Lupton, J.E., Scott, S.D., Tunnicliffe, V., Hammond, S.R., and McDuff, R.E., of the "CANADIAN AMERICAN SEAMOUNT EXPEDITION"
1985: Hydrothermal vents on an axis seamount of the Juan de Fuca Ridge; Nature, v.313, p.212-214.

Choukroune, P., Francheteau, J., et Hekinian, R.
1985: Carte géologique de la ride Est Pacifique à 12°50'N; Société Géologique de France, Bulletin, v.8, no.1, p.145-148.

Clague, D., Friesen, W., Quinterno, P., Morgenson, L., Holmes, M., Morton, J., Bouse, R., and Davis, A.
1984: Preliminary geological, geophysical, and biological data from the Gorda Ridge; U.S. Geological Survey Open-File Report 84-364, 49 p.

Clark, A., Johnson, C., and Chinn, P.A.
1984: Assessment of cobalt-rich manganese crusts in the Hawaiian, Johnston and Palmyra Islands' Exclusive Economic Zones; Natural Resources Forum, United Nations, New York, v. 8, no.2, p.163-174.

Clark, A.L., Humphrey, P., Johnson, C.J., and Pak, D.K.
1985: Cobalt-rich manganese crust potential; United States Department of the Interior, Minerals Management Service, OCS Study MMS 85-0006, 35 p.

Clauer, N., Hoffert, M. and Karpoff, A.-M.
1982: The Rb-Sr isotope system as an index of origin and diagenetic evolution of southern Pacific red clays; Geochimica et Cosmochimica Acta, v.46, p.2659-2664.

Corliss, J.B., Dymond, J., Gordon, L.I., Edmond, J.M., von Herzen, R.P., Ballard, R.D., Green, K., Williams, D., Bainbridge, A., Crane, K., and van Andel, T.H.
1979: Submarine thermal springs on the Galapagos Rift; Science, v.203, no. 4385, p.1073-1074.

Corliss, J.B., Lyle, M. and Dymond, J.
1978: The chemistry of hydrothermal mounds near the Galapagos Rift; Earth and Planetary Science Letters, v.40, p.12-15.

Cousens, B.L., Chase, R.L., and Schilling, J.-G.
1985: Geochemistry and origin of volcanic rocks from Tuzo Wilson and Bowie seamounts, northeast Pacific Ocean; Canadian Journal Earth Science, v.22, p.1609-1617.

Craig, H., Kim, K.-R., and Francheteau, J.
1983: Active ridge crest mapping on the Juan Fernandez Micro-Plate: The use of Seabeam-controlled hydrothermal plume surveys; EOS, v.64,no.45, p.856.

Craig, H., Kim, K.-R., and Poreda, R.
1986: Papatua 1986: A Grand Tour of the Havre Trough and the Lau, N.Fiji, Woodlark, and Manus Basins; EOS, v.67, no.16, p.378.

Crane, K., Aikman III, F., Embley, R., Hammond, S., Malahoff, A., and Lupton, J.
1985: The distribution of geothermal fields on the Juan de Fuca Ridge; Journal of Geophysical Research, v. 90, no.B1, p.727-744.

Cronan, D.S.
1972a: Composition of Atlantic manganese nodules; Nature, 235, p.171-172.

Cronan, D.S.
1972b: The Mid-Atlantic Ridge near 45°N, XVII: Al,As,Hg, Mn in ferruginous sediments from the Median Valley; Canadian Journal of Earth Sciences,v.4, p.319-323.

Cronan, D.S.
1977: Deep-sea nodules: distribution and geochemistry; in Marine Manganese Deposits, ed. G.P.Glasby; Elsevier Oceanographic Series, 15, Elsevier, Amsterdam, p.11-44.

Cronan, D.S.
1980: Underwater Minerals; Academic Press, London, 350 p., p.121, 195.

Cronan, D.S.
1983: Criteria for the recognition of areas of potentially economic manganese nodules and encrustations in the CCOP/SOPAC region of the Central and Southwestern Tropical Pacific; Technical Report No. 30, Economic and Social Commission for Asia and the Pacific, United Nations Development Programme, 50 p.

Cronan, D.
1985: A wealth of sea-floor minerals; New Scientist, 6 June 1985. p.34-38.

Cronan, D.S. and Varnavas, S.P.
1981: Hydrothermal and dissolution related geochemical variations in sediments from an East Pacific Rise fracture zone at 9°S; in Proceedings 26th International Geological Congress, Geology of oceans symposium, Paris; Oceanologica Acta, No.SP, p.47-58.

Cronan, D.S., Glasby, G.P., Moorby, S.A., Thomson, J., Knedler, K.E., and McDougal, J.C.
1982: A submarine hydrothermal manganese deposit from the southwest Pacific island arc; Nature, v.298, p.456-457.

Cronan, D.S., Hodkinson, R., Harkness, D.D., Moorby, S.A., and Glasby, G.P.
1986: Accumulation rates of hydrothermal metalliferous sediments in the Lau Basin, S.W.Pacific; Geo-Marine Letters, v.6, p.51-56.

Czamanske, G.K., and Moore, J.G.
1977: Composition and phase chemistry of sulfide globules in basalt from the Mid-Atlantic Ridge rift valley near 37°N lat; Geological Society of America, Bulletin, v.88, p.587-599.

Damuth, J.E.
1977: Late Quaternary sedimentation in the western equatorial Atlantic; Geological Society of America Bulletin, v.88. p.695-710.

Davis, E.E., Goodfellow, W.D., Bornhold, B.D., Adshead, J., Blaise, B., Villinger, H., and Le Cheminant, G.M.
1987: Massive sulfides in a sedimented rift valley, Northern Juan de Fuca Ridge;Earth and Planetary Science Letters, v.82., p.49-61.

Davis, E.E., Lister, C.R.B., Wade, U.S., and Hyndman, R.D.
1980: Detailed heat flow measurements over the Juan de Fuca Ridge system: Journal Geophysical Research, v.85 (B1), p.299-310.

Degens, E.T. and Ross, D.A. eds.
1969: Hot brines and recent heavy metal deposits in the Red Sea; Springer-Verlag New York Inc. 600 p.

Devine, J.D., and Leinen, M.
1981: Chemistry of the massive sulfide deposit cored at Site 471; in Yeats,R.S., Haq,B.U. et al.,Initial Reports of the Deep Sea Drilling Project, Volume 63, Washington, (U.S. Government Printing Office) p.679-685.

Duane, D.B.
1982: Elements of a proposed five-year research program on polymetallic sulfides; Marine Technology Society Journal, v.16, no.3, p.88.

Durga Prasada Rao, N.V.N., Behairy, A.K.A. and Al-Imam. O.A.O.
1984: Mineral phases and facies characterization in metalliferous sediments of Atlantis II Deep, Red Sea; Marine Geology, v.59, p.1-12.

Dymond, J., Corliss, J.B., Heath, G.R., Field, C.W., Dasch, E.J., and Veeh, H.H.
1973: Origin of metalliferous sediments from the Pacific Ocean; Geological Society of America Bulletin, v.84, p.3355-3372.

Edmond, J.M., Measures, C., McDuff, R.E., Chan, L.H., Collier, R., Grant, B., Gordon, L.I., and Corliss, J.B.
1979: Ridge crest hydrothermal activity and the balances of the major and minor elements in the ocean: The Galapagos Data; Earth and Planetary Science Letters, v.46, p.1-18.

Eldersfield, H.
1977: The form of manganese and iron in marine sediments; in Marine Manganese Deposits, ed. G.P.Glasby; Elsevier Oceanography Series, 15, Elsevier, Amsterdam, p.269-290.

El Wakeel, S.K. and Riley, J.P.
1961: Chemical and mineralogical studies of deep-sea sediments; Geochimica et Cosmochimica Acta, v.25, p.110-146.

Embley, R.W., Ganse, R., Malahoff, A., and Hammond, S.R.
1982: Tectonics of the Blanco Trough and Blanco-Juan de Fuca Intersection; EOS, v.63, no.45, p.1146.

Embley, R.W., Hammond, S., Malahoff, A., Ryan, W.F.B., Crane, K., and Kappel, E.
1983: Rifts of the southern Juan de Fuca; EOS, v.64, no.45, p.853.

Embley, R.W., Kulm, L., and Abbott, D.
1984: Kinematic and structural development of the Blanco Transform Zone; EOS, v.65, no.45, p.1110.

Exon, N.F.
1982: Offshore sediments, phosphorite and manganese nodules in the Samoan Region, Southwest Pacific; South Pacific Marine Geological Notes, Technical Secretariat, CCOP — SOPAC, ESCAP, SUVA, v.2, no.7, p.303-320.

Exon, N.F. and Cronan, D.S.
1983: Hydrothermal iron deposits and associated sediments from submarine volcanoes off Vanuatu, southwest Pacific; Marine Geology, v 52, p.M43-M52.

Francheteau, J., Needham, H.D., Choukroune, P., Juteau, T., Seguret, M., Ballard, R.D., Fox, P.J., Normark, W., Carranza, A., Cordoba, D., Guerrero, J., Rangin, C., Bougault, H., Cambon, P., and Hekinian, R.
1979: Massive deep-sea sulphide ore deposits discovered on the East Pacific Rise; Nature, v.277, p.523-525.

Frazer, J.Z.
1977: Manganese nodule reserves; an updated estimate; Marine Mining,v.1, no.1,2, p.103-123.

Frazer, J.Z. and Wilson, L.L.
1980: Manganese nodule resources in the Indian Ocean; Marine Mining, v.2, no.3, p.257-292.

Gente, P., Auzende, J.M., Renard, V., Fouquet, Y., and Bideau, D.
1986: Detailed geological mapping by submersible of the East Pacific Rise axial graben near 13°N; Earth and Planetary Science Letters, v.78, p.224-236.

Gillis, K.
1986: Leg 106 Summary; in Canadian National Committee Ocean Drilling Program Newsletter, Minister of State Mines, v.2, no.1

Glasby, G.P.
1977: Marine Manganese Deposits; Elsevier Oceanography Series, 15; Elsevier, Amsterdam, p.1-11.

Goldberg, E.D., and Arrhenius, G.O.S.
1958: Chemistry of Pacific pelagic sediments; Geochimica et Cosmochimica Acta, v. 13, p.153-212.

Goodfellow, W.D., Davis, E., Bornhold, B.D., Adshead, J.D., Blaise, B., and Le Cheminant, G.M.
1986: Massive sulphides discovered in a sedimented rift valley, Northern Juan de Fuca Ridge: Geological setting, mineralogy and geochemistry; Geological Survey of Canada, Paper 86-8, 1986 Current Activities Forum, Program with Abstracts.

Gray, J.J., and Kulm, L.D.
1985: Mineral resources map, offshore Oregon, scale 1:500 000; State of Oregon Department of Geology and Mineral Industries, U.S.A.

Greenslate, J.
1977: Manganese concentration wet density: A marine geochemistry constant; Marine Mining,v.1, No.1,2, p.125-148.

Greenslate, J., Frazer, J.Z., and Arrhenius, G.
1973: Origin and deposition of selected transition elements in the seabed; in Papers on the Origin and Distribution of Manganese Nodules in the Pacific and Prospects for Exploration, ed.M.Morgenstein; Hawaii Institute of Geophysics, p.45-70.

Grill, E.V., Chase, R.L., Macdonald, R.D., and Murray, J.W.
1981: A hydrothermal deposit from Explorer Ridge in the Northeast Pacific Ocean; Earth and Planetary Science Letters, v.52, p.142-150.

Gross, G.A.
1965: Geology of Iron Deposits in Canada, Volume 1, General Geology and Evaluation of Iron Deposits; Geological Survey of Canada, Economic Geology Report 22, p.82-132.

Gross, G.A.
1983: Tectonic systems and the deposition of iron-formation; Precambrian Research, v. 20, p.171-187.

Gross, G.A.
1986: The metallogenetic significance of iron-formation and related stratafer rocks; Journal Geological Society of India, v.28, p.92-108.

Gross, G.A., and McLeod, C.R.
1983: Worldwide distribution of ocean bed metallic minerals; Energy, Mines and Resources Canada, GEOS, v.12,no.3, Summer/Ete.

Halbach, P.
1982: Co-rich ferromanganese seamount deposits of the Central Pacific Basin; *in* Marine Mineral Deposits, Band,6 , eds. P.Halbach and P.Winter; Verlag Gluckauf GmbH.Essen. p.60-76.

Halbach, P.
1983: The polymetallic deposits of the deep-sea bottom within the Pacific Ocean; Monograph Series on Mineral Deposits 22, Gebruder Borntraeger, Berlin-Stuttgart. p.109-123.

Halbach, P. and Manheim, F.T.
1984: Potential of cobalt and other metals in ferromanganese crusts on seamounts of the Central Pacific Basin; Marine Mining, v.4, no.4, p.319-336.

Halbach, P.,Ozkara, M. and Hense, J.
1975: The influence of metal content on the physical and mineralogical properties of pelagic manganese nodules; Mineralium Deposita, v.10, no.4, p.397-411.

Hammond, S.R., Karsten, J., Davis, E., Currie, R., and Malahoff, A.
1983: Bathymetric and hydrothermal characterization of the northernmost Juan de Fuca Ridge; EOS, v. 64, no.45, p.853.

Hammond, S.R., Lee, J.S., Malahoff, A., Feeley, R., Embley, R.W., and Franklin, J.
1984: Discovery of high-temperature hydrothermal venting on the Endeavour Segment of the Juan de Fuca Ridge; EOS, v.65, no.45, p.1111.

Hannington, M.D., Peter, J.M., and Scott, S.D.
1985: Gold in seafloor polymetallic sulfide deposits; The Geological Society of America, 98th Annual Meeting, Abstracts with Programs 1985, p.602.

Hannington, M.D., Scott, S.D., and Chase, R.L.
1985: The Explorer Ridge polymetallic sulphide deposits: a major find in Canadian Pacific waters; Paper presented at the 16th Underwater Mining Institute, Halifax, Nova Scotia, October 1985.

Hawkins, J.
1986: "Black Smoker" vent chimneys; EOS, v.67, no.17, p.430.

Hawkins, J. and Helu, S.
1986: Polymetallic sulfide deposits from "black-smoker" chimney; Lau Basin; EOS, v.67, no.16, p.378.

Hayes, D.E., Pimm, A.C., Benson, W.E., Berger, W.H., Supko, P.R., Peckman, J.P. and Roth, P.H.
1972: Initial Reports of the Deep Sea Drilling Project, Volume XIV; Washington (U.S. Government Printing Office), p.49,85,135, 217.

Haynes, B.W., Law, S.L., Barron, D.C., Kramer, G.W., Maeda, R., Magyar, M.J.
1985: Pacific manganese nodules: characterization and processing; United States Department of the Interior, Bureau of Mines, Bulletin 679, 44 p.

Heath, G.R. and Dymond, J.
1977: Genesis and transformation of metalliferous sediments from the East Pacific Rise, Bauer Deep, and Central Basin, northwest Nazca plate; Geological Society of America Bulletin, v.88, p.723-733.

Heath, G.R., and Lyle, M.W.
1982: Modification of a hydrothermal sediment by suboxic diagenesis: evidence for manganese loss at MANOP Site (8°45'N, 104°W); EOS, v.63, no.45, p.999.

Hekinian, R.
1982: Petrology of the Ocean Floor; Elsevier Oceanography Series,33; Elsevier Scientific Publishing Company, Amsterdam-Oxford-New York. 393 p.

Hekinian, R. and Fevrier, M.
1979: Comparison between deep-sea hydrothermal deposits recovered from recent spreading ridges; in La Genese des Nodules de Manganese; Colloques Internationaux du Centre National de la Recherche Scientifique, no. 289, Editions du Centre National de la Recherche Scientifique, Paris, France. p.167-178.

Hekinian, R., Fevrier, M., Bischoff, J.L., Picot, P., and Shanks, W.C.
1980: Sulfide deposits from the East Pacific Rise near 21°N; Science, v.207, p.1433-1442.

Hekinian, R., and Fouquet, Y.
1985: Volcanism and metallogenesis of axial and off-axial structures on the East Pacific Rise near 13°N; Economic Geology, v.80, no.2, p.221-249.

Hoffert, M., Karpoff, A.M., Schaaf, A., and Pautot, G.
1979: The sedimentary deposits of the Tiki Basin (South-East Pacific), passage from carbonate oozes to "metalliferous sediments"; in La genèse des nodules de manganèse, Colloques Internationaux du Centre National de la Recherche Scientifique, No.289, Editions du Centre National de la Recherche Scientifique, Paris. p.101-112.

Honnorez, J., Honnorez-Guerstein, B., Valette, J., and Wauschkuhn, A.
1973: Present day formation of an exhalative sulfide deposit at Vulcano (Tyrrhenian Sea), Part II: Active crystallization of fumarolic sulfides in the volcanic sedimentations of the Baia di Levante; in Ores in Sediments, eds. G.C.Amstutz and A.J.Bernard; Springer-Verlag, Berlin, Heidelberg, New York, p.139-166.

Horowitz, A. and Cronan, D.S.
1976: The geochemistry of basal sediments from the North Atlantic Ocean; Marine Geology, v.20, p.205-208.

Ingle, J.C., Karig, D.E., Bouma, A.H., Ellis, C.H., Haile, N.S., Koizumi, I., McGregor, I., Moore, J.C., Ujiie, H., Watanabe, T., White, S.M.,Yasui, M., and Ling, H.Y.
1975: Initial Reports of the Deep Sea Drilling Project, Volume 31; Washington (U.S. Government Printing Office) p.49, 169.

Johnson, H.P., and Delaney, J.
1984: MERGE (Multidisciplinary Endeavour Ridge Geo-Expedition) in Northeast Pacific News, v.1, no.7, School of Oceanography, University of Washington, Seattle, 8 p.

Johnson, H.P., Karsten, J.L., Delaney, J.R., Davis, E.E., Currie, R.G., and Chase, R.L.
1983: A detailed study of the Cobb Offset of the Juan de Fuca Ridge: Evolution of a propagating rift; Journal of Geophysical Research, v.88, no.B3, p.2297-2315.

Jones, C.J., Johnson, H.P., and Delaney, J.R.
1981: Distribution of hydrothermal manganese over the Juan de Fuca Ridge; Geophysical Research Letters, v.8, p.873-876.

Kadko, D., Koski, R., Tatsumoto, M., and Bouse, R.
1985: An estimate of hydrothermal fluid residence times and vent chimney growth rates based on $^{210}Pb/Pb$ ratios and mineralogic studies of sulfides dredged from the Juan de Fuca Ridge; Earth and Planetary Science Letters, v.76, p.35-44.

Kadko, D., and Lupton, D.
1984: Radon-222 and temperature measurements on the Endeavor Ridge; EOS,v.65, no.45, p.974.

Karsten, J., Delaney, J., Johnson, P., Goldfarb, M., Kelley, D., McDuff, R., Tivey, M.K., Tivey, M., Dymond, J., Kadko, D., Taghon, G., Leinen, M., Lupton, J., Rhodes, M., Hey, D., and Tunnicliffe, V.
1984: Regional setting and local character of a hydrothermal field/sulfide deposit on the Endeavour Segment of the Juan de Fuca Ridge; EOS, v.65, no.45, p.1111.

Karsten, J.L., Hammond, S.R., Davis, E.E., and Currie, R.G.
1986: Detailed geomorphology and neotectonics of the Endeavour Segment, Juan de Fuca Ridge: New results from Seabeam swath mapping; Geological Society of America Bulletin, v.97, p.213-221.

Kong. L., Ryan, W.B.F., Mayer, L.A., Detrick, R.S., Fox, P.J., and Manchester, K.
1985: Bare-rock drill sites, O.D.P. Legs 106 and 109, evidence for hydrothermal activity at 25°N on the Mid-Atlantic Ridge; EOS,v.66, no.46, p.936.

Koski, R.A., Clague, D.A., and Oudin, E.
1984: Mineralogy and chemistry of massive sulfide deposits from the Juan de Fuca Ridge; Geological Society of America Bulletin, v.95, p.930-945.

Koski, R.A., Lonsdale, P.F., Shanks, W.C., Berndt, M.E., and Howe, S.S.
1985: Mineralogy and geochemistry of a sediment-hosted hydrothermal sulfide deposit from the Southern Trough of Guaymas Basin, Gulf of California; Journal of Geophysical Research, v.90, no.B8, p.6695-6707.

Koski, R.A., Normark, W.R., and Morton, J.L.
1985: Massive sulfide deposits on the Southern Juan de Fuca Ridge: Results of investigations in the USGS study area, 1980-83; Marine Mining, v.5, no.2, p.147-164.

Ku, T.L.
1977: Rates of accretion; in Marine Manganese Deposits, ed. G.P.Glasby, Elsevier Oceanographic Series 15, Elsevier, Amsterdam, p. 249-268.

Lalou, C., Brichet, E., Perez-Leclaire, H.
1984: The Galapagos hydrothermal mounds: history about 600,000 years to present; Oceanologica Acta, v.7, no.3, p.261-270.

Lalou, C., Brichet, E., Perez-Leclaire, C.J. and H.
1983: Hydrothermal manganese oxide deposits from Galapagos mounds, DSDP Leg 70, hole 509B and "Alvin" dives 729 and 721; Earth and Planetary Science Letters, v.63, p.63-75.

Lalou, C., Thompson, G., Rona, P.A., Brichet, E., and Jehanno, C.
1986: Chronology of selected hydrothermal Mn oxide deposits from the transatlantic geotraverse "TAG" area, Mid-Atlantic Ridge 26°N; Geochimica et Cosmochimica Acta, v.50, p.1737-1743.

Latouche, C., Maillet, N. and Bonté, P.
1979: Relations entre les caractéristiques minéralogiques des sédiments et les dépôts polymétalliques entre la zone de fracture Kane et le Grand Météor (Atlantique Nord-Est); in La Genèse des Nodules Manganèse; Colloques Internationaux du Centre National de la Recherche Scientifique, No.289, Editions du Centre National de la Recherche Scientifique, Paris, France. p.139-150.

Laughton, A.S., Berggren, W.A., Benson, R., Davies, T.A., Franz, U., Musich, L., Perch-Nielson, K., Ruffman, A., van Hinte, J.E., Whitmarsh, R.B., Aumento, F., Clarke, B.D., Cann, J.R., Ryall, P.J.C. and Burckle, L.H.
1972: Initial Reports of the Deep Sea Drilling Project, Volume XII, Washington (U.S. Government Printing Office) p.161, 673-751.

Leinen, M.
1981: Metal-rich basal sediments from Northeastern Pacific Deep Sea Drilling Project Sites; in Yeats,R.S., Haq,B.U., et al., Initial Reports of the Deep Sea Drilling Project, Volume 63, Washington (U.S. Government Printing Office) p.667-676.

Leinen, M.
1982: Late Pleistocene hydrothermal sedimentation at DSDP Leg 91 "HYDROGEOLOGY" sites; EOS, v.63, no.45, p.1135.

Leinen, M. and Anderson, R.N.
1981: Hydrothermal sediment from the Marianas Trough; EOS, v.62, no.45, p.914.

Levin, L.A. and Lonsdale, P.
1983: Hydrothermal and other faunas of submarine volcanoes at 20°N in the East Pacific Ocean; EOS, v.64, no.52, p.1017.

Lewis, B.T.R., Robinson, P.T., Benson, R.N., Blackinton, G., Cambon, P., Day, R., Duennebier, F., Flower, M.F.J., Gutierrez-Estrada, M., Hattner, J.G., Kudo, A.M., Morrison, M.A., Rangin, C., Salisbury, M.H., Schmincke, H.-U., Stephen, R., and Zolotarev, B.P.
1979: Initial Reports of the Deep Sea Drilling Project, Volume LXV, Washington (U.S. Government Printing Office), p.21-67.

Lonsdale, P.
1977: Deep-tow observations at the Mounds Abyssal Hydrothermal Field, Galapagos Rift; Earth and Planetary Science Letters, v.36, p.92-119.

Lonsdale, P., Batiza, R., and Simkin, T.
1982: Metallogenesis at seamounts on the East Pacific Rise; Marine Technology Society Journal, v.16, no.3, p.54-60.

Lonsdale, P.F., Bischoff, J.L., Burns, V.M., Kastner, M., and Sweeney, R.E.
1980: A high-temperature hydrothermal deposit on the seabed at a Gulf of California spreading center; Earth and Planetary Science Letters, v.49, p.8-20.

Lonsdale, P. and Hawkins, J.
1985: Silicic volcanism at an off-axis geothermal field in the Mariana Trough back-arc basin; Geological Society of America Bulletin, v.96, p.940-951.

Lupton, J.E., and Craig, H.
1981: A major Helium-3 source at 15°S on the East Pacific Rise; Science, v.214, no.4516, p.13-14.

Malahoff, A.
1981: Comparison between Galapagos and Gorda spreading centers; Paper presented at the 13th Annual Offshore Technology Conference, Houston,Texas, Preprint OTC 4129, p.115.

Malahoff, A.
1982: Massive enriched polymetallic sulfides of the ocean floor — a new commercial source of strategic minerals?; Paper presented at the 14th Annual Offshore Technology Conference, Houston, Texas, Preprint OTC 4293, p. v16-15 to v16-20.

Malahoff, A., Embley, R.W., Cronan, D.S., Skirrow, R.
1983: The geological setting and chemistry of hydrothermal sulfides and associated deposits from the Galapagos Rift at 86°W; Marine Geology, v.4, no.1, p.123-137.

Malahoff, A., McMurtry, G., Hammond, S., and Embley, R.
1984: High temperature fields - Juan de Fuca Ridge Axial Volcano; EOS, v.65,no.45, p.1112.

Malahoff, A., McMurtry, G.M., Wiltshire, J.C., and Yeh, Hsueh-Wen.
1982: Geology and chemistry of hydrothermal deposits from active submarine volcano Loihi, Hawaii; Nature, v.298, p.234-237.

Manheim, F.T.
1972: Composition and origin of manganese-iron nodules and pavements on the Blake Plateau; Papers from a conference on Ferromanganese Deposits on the Ocean Floor, ed. D.R.Horn; The Office for the International Decade of Ocean Exploration, National Science Foundation, Washington, D.C., p.105.

Manhiem, F.T.
1986: Marine cobalt resources; Science, v. 232, p.600-608.

Marchig, V., and Gundlach, H.
1982: Iron-rich metalliferous sediments on the East Pacific Rise: prototype of undifferentiated metalliferous sediments on divergent plate boundaries; Earth and Planetary Science Letters, v.58, p.361-382.

Marshall, J.F.
1983: Geochemistry of iron-rich sediments of the outer continental shelf off Northern New South Wales; Marine Geology, v.51, p.163-175.

Masson, D.G., Kidd, R.B. and Roberts, D.G.
1982: Late Cretaceous sediment sample from the Amirante Passage, western Indian Ocean; Geology, v. 10, p.264-266.

Maxwell, A.E., von Herzen, R.P., Andrews, J.E., Boyce, R.E., Milow, E.D., Hsu, K.J., Percival, S.F., and Saito, T.
1970: Initial Reports of the Deep Sea Drilling Project, Volume III, Washington (U.S. Government Printing Office) p.319,413.

McConachy, T.F., Ballard, R.D., Mottl, M.J., and Von Herzen, R.P.
1986: Geologic form and setting of a hydrothermal vent field at lat 10°56'N, East Pacific Rise: a detailed study using *Angus* and *Alvin*; Geology, v.14, p.295-298.

McConachy, T.F., Hannington, M.D., and Scott, S.D.
1985: Discovery of hydrothermal particle plumes on the Southern Explorer Ridge; EOS, v.66, no.46, p.929.

McDuff, R.E., Lupton, J.E., Kadko, D., and Lilley, M.D.
1984: Chemistry of hydrothermal fluids, Endeavour Ridge, Northeast Pacific; EOS, v.65,no.45, p.975.

McManus, D.A., Burns, R.E., von der Borch, C., Goll, R., Milow, E.D., Olsson, R.K., Vallier, T., and Weser, O.
1970: Initial Reports of the Deep Sea Drilling Project, Volume V; Washington (U.S.Government Printing Office) p.255,297.

McMurtry, G.M. and Burnett, W.C.
1975: Hydrothermal metallogenesis in the Bauer Deep of the southeastern Pacific; Nature, v.254, p.42.

McMurtry, G.M., Malahoff, A., Feely, R.A., and Massoth, G.J.
1984: Geology and chemistry of hydrothermal nontronite deposits from the Juan de Fuca Ridge; EOS, v.65, no.45, p.1112.

McMurtry, G.M., and Yeh, H.W.
1981: Hydrothermal clay mineral formation of East Pacific Rise and Bauer Basin sediments; Chemical Geology, v.32, p.189-205.

Mero, J.L.
1965: The Mineral Resources of the Sea; Elsevier, Amsterdam, 312 p.

Mero, J.L.
1977: Economic aspects of nodule mining; in Marine Manganese Deposits, ed. G.P.Glasby; Elsevier Oceanographic Series 15, p.327-356.

Meyer, K.
1973: Surface sediment and manganese nodule facies, ecountered on R/V Valdivia Cruises 1972//73; in Papers on the Origin and Distribution of Manganese Nodules in the Pacific and Prospects for Exploration, ed. M.Morgenstein; Hawaii Institute of Geophysics, Honolulu, Hawaii, July 23-25 1973. p.125-136.

Minniti, M. and Bonavia, F.F.
1984: Copper-ore grade hydrothermal mineralization discovered in a seamount in the Tyrrhenian Sea (Mediterranean): is the mineralization related to porphyry-copper or to base metal lodes? ; Marine Geology, v. 59, p. 271-282.

Minniti, M., Bonavia, F.F., Dacquino, C., Raspa, G.
1986: Distribution of Mn,Fe,Ni,Co, and Cu in young sediments of the Palinura Seamount in the Southeast Tyrrhenian Sea (Mediterranean); Marine Mining,v.5, no.3, p.277-305.

Moorby, S.A., Cronan, D.S., and Glasby, G.P.
1984: Geochemistry of hydrothermal Mn-oxide deposits from the S.W.Pacific island arc; Geochimica et Cosmochimica Acta, v.48, p.433-441.

Moore, W.S., and Vogt, P.R.
1976: Hydrothermal manganese crusts from two sites near the Galapagos spreading axis; Earth and Planetary Science Letters, v.29, p.349-356.

Morton, J.
1985: Massive sulfides recovered at Gorda Ridge; EOS, Transactions, American Geophysical Union, v.66, p.756.

Murnane, R., and Clague, D.A.
1983: Nontronite from a low-temperature hydrothermal system on the Juan de Fuca Ridge; Earth and Planetary Science Letters, v. 65, p.343-352.

Murray, J.
1878: On the distribution of volcanic debris over the floor of the ocean, — its character, source, and some of the products of its disintegration and decomposition; Proceedings of the Royal Society of Edinburgh, v.9, p.247-261.

Murray, J., and Irvine, R.
1895: On the manganese oxides and manganese nodules in marine deposits; Transactions of the Royal Society of Edinburgh, v.37, p.721-742.

Murray, J., and Renard, A.F.
1891: Report on the deep sea deposits; In, C.Wyville Thompson, (Ed.) Report of the voyage of the H.M.S. Challenger; Eyre and Spottiswood, London, p.525.

Normark, W.R., Morton, J.L., Holcomb, R.T., and Franklin, J.M.
1983: Southern Juan de Fuca Ridge revisited: A new evaluation of the distribution of hydrothermal activity, sulfide mineral deposits, and volcanic features; EOS, V.64, no.45, p.857.

Normark, W.R., Morton, J.L., Koski, R.A., and Clague, D.A.
1983: Active hydrothermal vents and sulfide deposits on the southern Juan de Fuca Ridge; Geology, v.11, p.158-163.

Oudin, E., Thisse, Y. and Ramboz, C.
1984: Fluid inclusion and mineralogical evidence for high-temperature saline hydrothermal circulation in the Red Sea metalliferous sediments: preliminary results; Marine Mining, v.5, no.1, p.3-31.

Pautot, G., Guennoc, P., Coutelle, A. and Lyberis, N.
1984: Discovery of a large brine deep in the northern Red Sea; Nature, v.310, p.133-136.

Peterson, M.N.A., von der Borch, C., Cita, M.B., Gartner, S., Goll, R., and Nigrini, C.
1970: Initial Reports of the Deep Sea Drilling Project, Volume II; Washington (U.S. Government Printing Office) p.35, 117.

Phillips, J.D., Thompson, G., Von Herzen, R.P. and Bowen, V.T.
1969: Mid-Atlantic Ridge near 43°N Latitude; Journal of Geophysical Research, v.74, p.3069-3077.

Piper, D.Z., Veeh, H.H., Bertrand, W.G., and Chase, R.L.
1975: An iron-rich deposit from the Northeast Pacific; Earth and Planetary Science Letters, v.26, p.114-120.

Puchelt, H.
1973: Recent iron sediment formation at the Kameni Islands, Santorini (Greece); in Ores in Sediments, eds. G.C.Amstutz and A.J.Bernard; International Union of Geological Sciences, Series A, No. 3, Springer-Verlag, Berlin, Heidelberg, New York, p.227-245.

Raab, W.J. and Meylan, M.A.
1977: Morphology; in Marine Manganese Deposits, ed. G.P.Glasby, Elsevier Oceanographic Series 15, Elsevier, Amsterdam, p.109-146.

Riddihough, R.P., Currie, R.G., and Hyndman, R.D.
1980: The Dellwood Knolls and their role in triple junction tectonics off northern Vancouver Island; Canadian Journal of Earth Science, v.17, p.577-593.

Ridout, P.S., Carpenter, M.S.N., and Morris, R.J.
1984: Analysis of a metalliferous encrustation from a seamount in the Gulf of Guinea; Chemical Geology, v.42, p. 219-225.

Rona, P.A.
1980a: TAG hydrothermal field: Mid-Atlantic Ridge crest at latitude 26°N; Journal Geological Society of London,v.137, p.385-402.

Rona, P.A.
1980b: NOAA Atlas 3, The Central North Atlantic Ocean Basins and Continental Margins: Geology, Geophysics, Geochemistry, and Resources, Including the Trans-Atlantic Geotraverse (TAG); U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Research Laboratories, Miami, Florida.

Rona, P.A.
1985: Hydrothermal mineralization at slow spreading centers: Red Sea, Atlantic Ocean, and Indian Ocean; Marine Mining, v.5, no.2, p.117-146.

Rona, P.A.
1986: Marine Data Miner, v.2, no.1, p.2.

Rona, P.A., and Claque, D.A.
1986: Geologic setting of hydrothermal activity at the Northern Gorda Ridge; EOS, v.67, no.44, p.1028.

Rona, P.A., Boström, K., Widenfalk, L., Cronan, D.S., and Jenkins, W.J.
1984: Asymmetric hydrothermal activity and tectonics of the Mid-Atlantic Ridge, 11° to 26° North; EOS,v.65, no.45,p.974.

Rona, P.A., Boström, K., Widenfalk, L.E.G., Mallette, M., and Melson, W.B.
1981: Preliminary reconnaissance of the Carlsberg Ridge, Northwestern Indian Ocean, for hydrothermal mineralization; EOS, Transactions, American Geophysical Union, v.62,no.45, p.914.

Rona, P.A., Harbison, R.H., Bassinger, B.G., Scott, R.B., and Nalwalk, A.J.
1976: Tectonic fabric and hydrothermal activity of Mid-Atlantic Ridge crest (lat. 26°N); Geological Society of America,Bulletin, v.87, p.661-674.

Rona, P.A., Klinkhammer, G., Nelsen, T.A., Trefry, J.H., and Elderfield, H.
1986: Black smokers, massive sulphides and vent biota at the Mid-Atlantic Ridge; Nature, v.321, p.33-37.

Rowland, R.W., Goud, M.R., and McGregor, B.A.
1983: The U.S. Exclusive Economic Zone- A summary of its geology, exploration, and resource potential; United States Department of the Interior, Geological Circular 912, 29p.

Sayles, F.L. and Bischoff, J.L.
1973: Ferromanganoan sediments in the equatorial East Pacific; Earth and Planetary Science Letters, v.19, p.330-336.

Sayles, F.L., Ku, T.-L., and Bowker, P.C.
1975: Chemistry of ferromanganoan sediment of the Bauer Deep; Geological Society of America Bulletin, v. 86, p.1423-1431.

Schrader, E.L., Rosendahl, B.R., Furbish, W.J., and Mattey, D.P.
1980: Mineralogy and geochemistry of hydrothermal and pelagic sediments from the Mounds Hydrothermal Field, Galapagos Spreading Center: DSDP Leg 54; Journal of Sedimentary Petrology, v.50, no.3, p.0917-0928.

Scott, S.D.
1985: Seafloor polymetallic sulphide deposits: Modern and Ancient; Marine Mining, v.5, no.2, p.191-212.

Scott, S.D., Barrett, T.J., Hannington, M., Chase, R.L., Fouquet, Y., and Juniper, K.
1984: Tectonic framework and sulfide deposits of Southern Explorer Ridge, Northeastern Pacific Ocean; EOS, v.65, no.45, p.1111.

Selk, B.W.
1982: Sedimentary evidence for hydrothermal activity in the Blanco Fracture Zone; EOS, v.63,no.45, p.1146.

Shanks, W.C.
1982: Economic and exploration significance of Red Sea metalliferous brine deposits; Society of Mining Engineers of AIME, Preprint number 82-116.7p.

Simoneit, B.R.T.
1985: Hydrothermal petroleum: genesis, migration, and deposition in Guaymas basin, Gulf of California; Canadian Journal of Earth Science, v.22, p.1919-1929.

Smith, P.A. and Cronan, D.S.
1983: The geochemistry of metalliferous sediments and waters associated with shallow submarine hydrothermal activity (Santorini, Aegean Sea); Chemical Geology, v.39, p.241-262.

Sorem, R.K. and Fewkes, R.H.
1977: Internal characteristics; in Marine Manganese Deposits, ed. G.P.Glasby; Elsevier Oceanographic Series 15, Elsevier, Amsterdam, p.147-184.

Stoffers, P., Lallier-Verges, E., Pluger, W., Schmitz, W., Bonnot-Courtois, C., and Hoffert, M.
1985: A "Fossil" hydrothermal deposit in the South Pacific; Marine Geology, v.62, p.133-151.

Stout, P.M., and Campbell, A.C.
1983: Hydrothermal alteration of near-surface sediments, Guayamas Basin, Gulf of California: Preprint from Symposium on Cenozoic Marine Sedimentation-Pacific Margin,ed.D.K.Lalue. Society of Economic Paleontologists and Mineralogists, p.223-231.

Styrt, M.M., Brackmann, A.J., Holland, H.D., Clark, B.C., Pisutha-Arnond, V., Eldridge, C.S., and Ohmoto, H.
1981: The mineralogy and the isotope composition of sulfur in hydrothermal sulfide/sulfate deposits on the East Pacific Rise, 21°N latitude; Earth and Planetary Science Letters, v.53, p.382-390.

Thompson, G., Woo, C.C., and Sung, W.
1975: Metalliferous deposits on the Mid-Atlantic Ridge; Abstracts with Programs, 1975 Annual Meetings, The Geological Society of America, v.7, no.7, p.1297.

Thomson, C.W., and Murray, J.
1895: Report on the scientific results of the voyage of H.M.S. *Challenger*, 1872-76, A summary of the scientific results, Part I and II; Eyre and Spottiswoode, London, p.1608.

Tivey, M.K., and Delaney, J.R.
1986: Growth of large sulfide structures on the Endeavour Segment of the Juan de Fuca Ridge; Earth and Planetary Science Letters, v.77, p.303-317.

Tunnicliffe, V.
1983: Life at the top: Hydrothermal vent communities on Axial Seamount, Juan de Fuca Ridge (46°N); EOS, v.64, p.1017.

Tunnicliffe, V., Johnson, H.P., and Botros, M.
1984: Along-strike variation in hydrothermal activity on Explorer Ridge, N.E. Pacific EOS, .65, no.45, p.1124.

Tucholke, B.E., Vogt, P.R. et al.,
1979: Initial Reports of the Deep Sea Drilling Project, Volume 43; Washington (U.S. Government Printing Office) 1115 p.

Valette-Silver, J.N.
1981: Influence of a hydrothermal system on submarine mineral neogenesis: the model of Vulcano Island (Italy); EOS v.62,no.17, p.423.

Varnavas, S.P., and Cronan, D.S.
1981: Partition geochemistry of sediments from DSDP 424 in the Galapagos Hydrothermal Mounds Field; Mineralogical Magazine, v.44, p.325-331.

Volpe, A., Lougee, B. and Hawkins, J.
1986: Petrologic-tectonic evolution of the Lau Basin; EOS, v.67, no.16, p.378.

von der Borch, C.C., Nesteroff, W.D., and Galehouse, J.S.
1971: Iron-rich sediments cored during Leg 8 of the Deep Sea Drilling Project; in Tracey,J.I.,Jr., et al., Initial Reports of the Deep Sea Drilling Project, Volume VIII, Washington (U.S. Government Printing Office) p.829-836.

von der Borch, C.C., and Rex, R.W.
1970: Amorphous iron oxide precipitates in sediments cored during Leg 5, Deep Sea Drilling Project; in McManus,D.A., et al., 1970, Initial Reports of the Deep Sea Drilling Project, Volume V. Washington (U.S. Government Printing Office) p.541-544.

von der Borch, C.C., Slater, J.G., Gartner Jr., S., Hekinian, R., Johnson, D.A., McGowran, B., Pimm, A.C., Thompson, R.W., Veevers, J.J., and Waterman, L.S.
1974: Initial Reports of the Deep Sea Drilling Project, Volume 22, Washington (U.S. Government Printing Office) p.85,194.

von Stackelberg, U., Gastner, M., Glasby, G.P., Gundlach, H., Johnson, K., Lettau, O., Lum, J., Marchig, V., Morton, J.L., Pohl, W., von Rad, U., Riech, V., Schmitz, W., Stoffers, P., and Wiedicke, M.
1985: Hydrothermal sulfide deposits in back-arc spreading centers in the Southwest Pacific; Bundesanstalt fur Geowissenschaften und Rohstoffe, Circular 2, Hannover. 14 p.

Walker, J.A., Ryall, P.J.C., and Zentilli, M.
1984: The origin of compositional variation in basalts recovered by submersible drill from Mount Glooscap, Mid-Atlantic Ridge at 36°25'N; Canadian Journal of Earth Science, v.21, p.934-948.

Walter, P. and Stoffers, P.
1985: Chemical characteristics of metalliferous sediments from eight areas on the Galapagos Rift and East Pacific Rise between 2°N and 42°S; Marine Geology, v.65, p.271-287.

Williams, D.L., Green, K., van Andel, T.H., Von Herzen, R.P., Dymond, J.R., and Crane, K.
1979: The hydrothermal mounds of the Galapagos Rift: Observations with DSRV *Alvin* and detailed heat flow studies; Journal of Geophysical Research, v.84, no.B13, p.7467-7469.

Winterer, E.L., Riedel, W.R.A., Moberly, R.M. Jr., Resig, J.M., Kroenke, L.W., Gealy, E.L., Heath, G.R., Erlend, M., and Worsley, T.R.
1971: Initial Reports of the Deep sea Drilling Project, Volume VII; Washington (U.S. Government Printing Office) p.725-729.

Yeats, R.S., Haq, B.U., Barron, J.A., Bukry, D., Crouch, J., Denham, C., Douglas, A.G., Grechin, V.I., Leinen, M., Niem, A., Verma, S.P., Pisciotto, K.A., Poore, R.Z., Shibata, T., and Wolfart, R.
1981: Site 471: Offshore Magdalena Bay; Initial Reports of the Deep Sea Drilling Project, Volume 63, Washington (U.S.Government Printing Office) p.269-270.

Zierenberg, R.A. and Shanks III, W.C.
1983: Mineralogy and geochemistry of epigenetic features in metalliferous sediment, Atlantis II Deep, Red Sea; Economic Geology, v.78, p.57-72.